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# A Plug-and-Play Duct System Evaluation

July 2017

Building AMERICA

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# A Plug-and-Play Duct System Evaluation

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July 2017

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The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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## Definitions

| | |
|---|---|
| ABS | acrylonitrile butadiene styrene |
| ACCA | Air Conditioning Contractors of America |
| ACH50 | air change per hour at 50 Pa |
| AFN | Airflow Network |
| AHU | air handling unit |
| ASHRAE | American Society of Heating, Refrigerating, and Air-Conditioning Engineers |
| CFM | cubic feet per minute |
| ELA | effective leakage area |
| HVAC | heating, ventilating, and air conditioning |
| IECC | International Energy Conservation Code |
| NURBS | Nonuniform Rational Basis Spline |
| PEX | cross-linked polyethylene |
| PnP | Plug and Play |
| PVC | polyvinyl chloride |

# Executive Summary

This report describes an air distribution system composed of a series of uniformly-sized ducts that terminate in rooms throughout the home and return to a central manifold, similar in fashion to a "home-run" cross-linked polyethylene plumbing system. With a well-designed manifold, each duct receives an equal static pressure potential for airflow from the air handling unit, and the number of needed ducts for each room are simply attached to fittings located on the manifold; in this sense, the system is plug-and-play (PnP). As indicated, all ducts in the PnP system are identical in size and small enough to fit in the ceiling and wall cavities of a house (i.e., less than 3.5-in. outer diameter). These ducts are also more appropriately sized for the lower airflow requirements of modern, energy-efficient homes; therefore, the velocity of the air moving through the duct is between that of conventional duct systems (approximately 700 ft/min) and high-velocity systems (more than 1,500 ft/min) on the market today. The PnP duct system uses semi-rigid plastic pipes, which have a smooth inner wall and are straightforward to install correctly, resulting in a system that has minimal air leakage. However, plastic ducts are currently not accepted by code for use in residential buildings; therefore, the project team considered other duct materials for the system that are currently accepted by code, such as small-diameter, wire-helix, flexible ductwork.

Figure 1 illustrates a PnP conceptual diagram. All ducts emanate from a central distribution manifold.

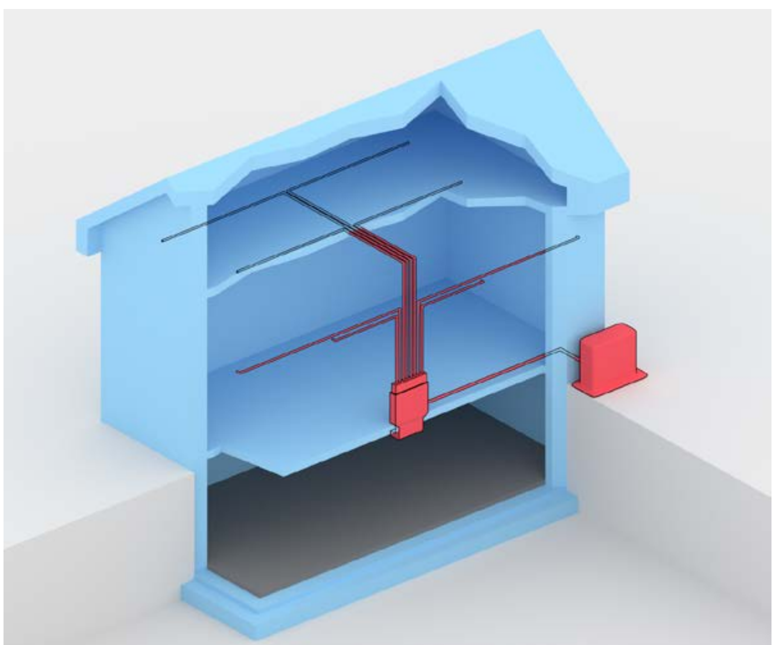

**Figure 1. PnP conceptual diagram**

A new design methodology for the PnP duct system was developed as part of this project because existing duct design methods are not optimized for the PnP home-run approach. For this new methodology, a designer would use a calculation spreadsheet that selects the number of equal-sized ducts needed to condition each zone. The number of ducts needed would be based on the heating and cooling loads calculated for each zone and the total length of the ducts and number of elbows needed to reach each zone. Adjustments to the design airflows would be made based on the type of duct material selected.

Lab testing and modeling were completed to determine the appropriate materials and duct diameters needed to adequately condition homes built to the 2009 and 2012 International Energy Conservation Code enclosure requirements (IECC 2009; IECC 2012). Most homes up to 4,200 $ft^2$ in climate zones 3–5 could be adequately conditioned with 3-in.-diameter smooth ductwork, and smaller homes (less than 2,200 $ft^2$) or homes that have a very small space-conditioning load (built to certification standards of the Passive House Institute US[1]) could be conditioned using 2.5-in. or 2-in. smooth ductwork.

Cost is a key consideration for any new product introduced to the building market. The material and labor costs to install the PnP system compared to those of a traditional trunk-and-branch system were evaluated and are shown in Table 1. A complete description and breakdown of these costs can be found in the Time and Motion Study and Cost Analysis section (Section 3).

**Table 1. System Cost Summary**

| System | Labor (h) | Materials ($) | Total ($) |
| --- | --- | --- | --- |
| Trunk-and-branch | 18 | 487 | 1076 |
| 2.5-in. PnP | 10 | 681 | 1012 |
| 2-in. PnP | 6 | 440 | 635 |

The performance of the PnP system was evaluated against a traditional trunk-and-branch system in achieving temperature uniformity throughout a house when compared to the set point of a central thermostat. To complete this evaluation, a detailed EnergyPlus[2] model was developed that consisted of a multizone geometry model with an Airflow Network (AFN) model to simulate the forced-air distribution system and natural air mixing and infiltration. The modeling compared well to measured data from an installed test system, with a 15% root mean square error for the period of comparison and with no individual room's predicted temperature exceeding a 9% root mean square error. Results from the simulation effort showed that the PnP duct system performs similarly to or better than a traditional trunk-and-branch system.

Both the PnP and trunk-and-branch systems struggled to maintain comfort in Climate Zone 5 in the heating season because of excessive airflow, which is a result of the imbalance between heating and cooling loads and required airflows. This imbalance highlights the need for duct systems in lower load homes located in cooler climates to be seasonally rebalanced to ensure optimal comfort in the home.

In addition to the technology development, another goal of the project was to engage the industry and solicit feedback on the PnP duct concept to the residential housing industry. The primary goals of the market engagement activities were to gain interest, acceptance, and demand for the

[1] http://www.phius.org/phius-certification-for-buildings-and-products
[2] https://energyplus.net/

PnP air delivery system. Primary market engagement activities included gaining an understanding of builder attitudes and values, identifying building code obstacles, understanding consumer attitudes and values, presenting material at industry events, securing builder commitment to demonstrate the PnP technology, and securing manufacturer commitment to commercialize the technology.

For the PnP system, outcomes of the market engagement activities demonstrated real interest in the technology and highlighted key areas where this technology could help builders improve performance and increase profit. In places where codes and regulations are pushing for higher performance and requiring ductwork to be installed inside conditioned space (such as in California, per Title 24[3]), the PnP system could be a cost-effective means to achieve these required targets. With reduced labor needed to install and commission the PnP system, builders and their trades can reduce costs while achieving acceptable comfort in their homes. The primary barrier to the development and adoption of the PnP system is the current code barrier regarding the use of plastic ductwork, which must be addressed before the full potential of this system can be realized; however, alternate duct materials can be used to advance the technology while this code barrier is being addressed.

[3] http://www.energy.ca.gov/title24/

# 1 Background

A need exists in the home building industry for innovative new approaches to space-conditioning technology. One such need is for improved air delivery (i.e., duct) systems. Current tools and practices require trade contractors to design air delivery systems that are often complex, difficult to install and integrate into the framing and structural components of the home, and not optimized for newer space-conditioning equipment or for the comfort needs of more energy-efficient homes. This complex process can be a burden to an already-strained construction labor pool; and it has been shown to lead to comfort problems in homes, negatively impacting the homeowner, trade contractor, manufacturer of the equipment, and builder. This report investigates a technology that promises to simplify duct system design and eliminate many sources of installation error for residential air delivery systems.

Energy-efficient homes have significantly lower heating and cooling load requirements to maintain comfort. Modern space-conditioning equipment offsets these loads primarily by using heated or cooled and dehumidified air. As the thermal load for a home is reduced, so is the amount of air required for space conditioning. IBACOS has conducted research during the last 25 years on the effectiveness of air delivery systems. Recently, IBACOS considered various simplified space-conditioning systems and their ability to provide comfort in an unoccupied test house (Poerschke and Stecher 2014). The conclusion of this work is that some amount of conditioned air should be delivered directly to each zone or room in the home to maintain thermal uniformity throughout the home when a centrally-located thermostat is used. To deliver this air, IBACOS considered using small-diameter ducts coupled with a variable-capacity heat pump (Poerschke 2015). This equipment provided the expected level of temperature uniformity; however, the installation of the duct system still required careful design and installation using conventional methods. In this test system, the small-diameter ducts had the added benefit of providing more effective mixing of the conditioned air in the zone than a control system using traditionally sized ducts.

The goal of this project was to develop a simplified residential air delivery system that is a solution to air distribution and comfort delivery issues in low-load, production-built homes and is emergent on the industry. The specific objectives included the following:

- Develop a straightforward design methodology and companion guidance documents that will allow a heating, ventilating, and air-conditioning (HVAC) technician to quickly produce the equivalent of an engineered design for a simple, field-assembled, small-diameter, rigid-material residential duct system, presently called the plug-and-play (PnP) air delivery system.
- Demonstrate the advantages of the simplified air delivery system compared to traditional trunk-and-branch residential duct systems.
- Demonstrate tangible progress to overcoming code and standard barriers associated with implementing this technology in residential buildings.
- Secure written commitment from at least one manufacturer partner to pursue product development and at least one builder partner to demonstrate the technology based on preliminary findings.

Responding to the increasing presence of high-performance homes in the marketplace, the PnP design methodology and related documents will serve a quickly-developing industry need. The need is for conventionally-skilled tradespersons and home designers to have a quick, efficient, credible method for designing an air delivery system that responds to the unique qualities of low-load homes and emerging comfort systems and provides reliable design results.

Advantages of the PnP system are likely to relate to performance, integration in the conditioned space of the house, constructability, cost, and value. Validating the advantages of the PnP system compared to trunk-and-branch duct systems is critical to gaining its acceptance by stakeholders such as builders, installers, home designers, and product manufacturers.

To be positioned to overcome the anticipated code and standard barriers associated with implementing this technology as soon as possible, code officials, code jurisdictions, and other stakeholders and industry groups must understand the technical justification for this system, the associated costs, and how the system will support occupant safety and the health mission of the codes. Achieving buy-in from the code body will help increase the speed at which this approach to air delivery can be adopted by the industry by facilitating the approval process during the planning and construction of new homes.

The PnP approach must prove to be viable for production-built, low-load homes. The viability of the PnP approach will be shown if and when its advantages are validated, the design methodology is developed and useable, and tangible progress toward overcoming code and standard barriers is demonstrated. Commitment from a manufacturer partner to commercialize this technology and interest from builders to use the technology in homes are critical for the success of this new system in the market.

As a partner in this project, IBACOS engaged with the Housing Innovation Alliance (Alliance), formerly a program within IBACOS and now a separate limited liability corporation. The Alliance is composed of participants from every aspect of the housing value chain. Its members are some of the most forward-looking builders, developers, and suppliers in the industry, and they have some of the sharpest minds in sales and marketing, architecture and design, land and community development, finance and appraisals, business and quality management, technology, home performance, real estate, sustainability, and other key disciplines. The Housing Innovation Alliance fosters the development of collaborative insights that address business pains today and accelerates innovations that will change the housing industry moving forward.

# 2 Design Methodology Development

A design methodology for the PnP duct system was developed as part of this project because existing duct design methods are not appropriate for the PnP home-run (i.e., all ducts emanating from a central manifold) approach. Using this new methodology, a designer would use a calculation spreadsheet that selects the number of equal-sized ducts needed to condition each zone. The number of ducts would be based on the heating and cooling loads calculated for each zone and the estimated total length of the ducts and number of elbows needed to reach each zone. Adjustments to the design airflows would be made based on the type of duct material selected.

## 2.1 Design Methodology Concept

The intent of the design methodology is to streamline the standard process of designing a residential duct system and to provide a design approach that is specific to the PnP duct system. Current design practices are suitable for duct systems composed of different duct diameters and materials as well as fitting types. A typical residential trunk-and-branch duct system might have more than 40 unique components, including trunks, takeoff boots, elbows, branch ducts, register boots, and registers. The impact of each of these pieces must be considered when designing the overall system. The proposed PnP duct system can be assembled from 2–5 unique airflow components, including a single duct diameter, single elbow, and register.

Because the PnP duct system uses only a single duct diameter to account for variations in zone loads, the number of duct runs to each zone must vary. The primary purpose of this design methodology is to define the process by which the number of ducts to each room is determined. This process is different from standard approaches, wherein the duct diameter is varied depending on the zone's load and resulting airflow needs.

The design method was developed to provide a balance between ease of use and accuracy. The design method incorporates existing industry standards and uses coefficients derived from lab measurements collected during this project.

The design method that was developed accounts for the duct length and number of elbows, but it does not consider the impact of thermal losses along the length of the duct. This approach is similar to the Air Conditioning Contractors of America (ACCA) *Manual D*'s assumptions for ductwork in conditioned space. Accounting for thermal losses is challenging, even for advanced simulation tools, and achieving accurate results is not a trivial process. Heat convection away from a duct depends on the shape of duct, orientation of ductwork (horizontal/vertical), and ambient conditions. A single duct in a floor cavity will have much more thermal loss than a pack of several ducts in a vertical stud bay. Additionally, the energy lost from the ductwork ends up in conditioned zones through radiation, conduction, and convection. Exactly how the energy is distributed to surrounding materials and zones can be difficult to predict.

An outline of the design process follows. The complete design method is included in Appendix B.

1. Complete ACCA *Manual J* load sizing for each room of the home.

2. Create a rough duct layout using the home's floor plan, and determine approximate duct lengths to air handling unit (AHU) closet and number of elbows. Duct routing should be compact, with outlets located on interior walls, throwing toward exterior walls. Framing plans should be referenced to understand the direction of floor joists and size of cavities. These factors must be considered by the system designer.

3. Determine available static pressure using ACCA *Manual S* (which is typically required by code) (Rutkowski 1995; Rutkowski 2009a).

4. Enter values in design method spreadsheet.

5. Spreadsheet determines the total number of ducts to each zone.

The design spreadsheet calculates the airflow through each duct based on the duct type selected (2-in. and 2.5-in. polyvinyl chloride [PVC] and 3.0-in. flex duct), length, number of elbows, and available static pressure. It is assumed that the static pressure is identical for each duct inlet. Past Building America research shows that this is an appropriate assumption for ideal manifold box designs (Poerschke and Rudd 2015). The following equation is used to calculate airflow based on total equivalent length. This equation (Eq. 1) is a rearranged form of the generic flow-versus-pressure power law (ASHRAE 2005, 35.14, Eq. 37).

$$Q = \frac{Pa}{C * L}^{\frac{1}{n}} \qquad (1)$$

where $Q$ is the volumetric flow rate, $Pa$ is the pressure available to the duct system after all other system losses have been accounted for, $C$ is the flow coefficient, $n$ is the flow exponent, and $L$ is the duct length.

The values for the flow coefficient, $C$, and the flow exponent, $n$, are derived from laboratory measurements for each duct material. These values are presented for various materials in the Table 3 in Section 2.2 of this report.

Once the flow per duct runout has been calculated, the spreadsheet calculates the total energy delivery per duct by multiplying the volumetric flow rate by the predetermined heating and cooling factors. For the PnP system, a heating factor of 0.0231 Btuh/CFM is assumed, and a cooling factor of 0.0268 Btu/h·CFM (320 CFM/t) is assumed. The assumed cooling factor is lower than that of standard equipment and more in line with small-diameter duct systems. These numbers depend on the specific equipment chosen, but they provide a reasonable starting point. The design heating and cooling load is divided by the respective energy delivery per duct and rounded to the nearest integer number. A zone that requires 1.4 times the airflow of a single duct will receive only a single duct. A zone that requires 1.6 times the airflow of a single duct will receive two ducts. The greater of the heating and cooling ducts is then selected as the design number.

Figure 2 shows a sample of the design method spreadsheet. The heating and cooling loads for several rooms in a small house are shown, along with the estimated duct lengths and elbows. The spreadsheet calculated the number of ducts needed for each room. Further explanation of the spreadsheet can be found in Appendix B.

**Plug-and-Play Home Run Manifold Design Tool**

v 0.1

Project

| | | |
|---|---|---|
| Nominal CFM | 26 | (based on 30' L, 60 Pa) |
| Available Pressure | 0.35 | in. wc. (from manual S) (minus 0.1" for manifold) |
| Heating factor | 0.0231 | Btuh / CFM |
| Cooling factor | 0.0268 | Btuh / CFM |

| # | Room | Htg Load (Btuh) | Clg Load (Btuh) | CFM | Len (ft.) | Elb | Ducts |
|---|---|---|---|---|---|---|---|
| 1 | Master Bedroom | 2365 | 2316 | 55 | 29 | 5 | 2 |
| 2 | Bath 2 | 642 | 220 | 15 | 12 | 3 | 1 |
| 3 | Bedroom 2 | 2025 | 1500 | 47 | 15 | 4 | 2 |
| 4 | Powder | 798 | 620 | 18 | 22 | 3 | 1 |
| 5 | 1st Floor | 6489 | 4486 | 150 | 16 | 3 | 5 |
| 6 | | | | | | | |
| 7 | | | | | | | |
| 8 | | | | | | | |
| 9 | | | | | | | |
| 10 | | | | | | | |
| 11 | | | | | | | |
| 12 | | | | | | | |
| 13 | | | | | | | |
| 14 | | | | | | | |
| 15 | | | | | | | |
| 16 | | | | | | | |
| | Total: | 12319 | 9142 | 285 | 94 | 18 | 11 |

Select Material

2" PVC

| | |
|---|---|
| EL of 90 | 2 |
| Pipe Diameter | 2.0 |

Coefficients – 2" PVC  CFM = (Pa/C*L)^(1/n)

| | |
|---|---|
| C | 0.01146 |
| n | 1.70239 |

**Figure 2. Sample design method spreadsheet**

## 2.2 Component Testing

To understand the performance of various duct materials, lab testing was conducted to characterize the pressure and airflow relationships of these materials. These results were used in the design methodology calculations and as a guide for understanding what materials and diameters are appropriate to adequately condition homes built to the International Energy Conservation Code (IECC) 2009 and 2012 enclosure requirements.

### *2.2.1 Airflow in a Pipe*

The flow of fluid through pipes is a well-understood phenomenon. Any fundamental fluid dynamic materials can more than adequately describe the flow resistance through a pipe network

(Munson et al. 2009). Using the Darcy-Weisbach equation, the pressure drop through a given straight pipe can be determined at a given flow rate (Eq. 2):

$$\Delta p = f\frac{\ell}{D}\frac{\rho V^2}{2} \tag{2}$$

where $f$ is the friction factor, $l$ is the duct length, $D$ is the duct diameter, $\rho$ is the fluid density, and $V$ is the fluid velocity.

Despite the seeming straightforwardness of this equation, empirically-derived coefficients for pipe roughness must be determined to calculate the friction factor. The purpose of this work is to understand these coefficients under conditions expected for residential air delivery.

Fittings do not have a straightforward equation such as Darcy-Weisbach, and coefficients must be derived using experimental data for each fitting. Loss coefficients exist for many standard duct fittings; however, they do not exist not for small-diameter, rigid-plastic pipe used for airflow. Another aspect of this lab testing is to gather the data necessary to understand the resistance-versus-flow relationship for small-diameter plastic duct fittings.

A complicating factor for the expected duct runout designs is the interaction between adjacent fittings (elbows). It is accepted that flow will become fully developed through 10 diameters of pipe length (Munson et. al. 2009). In a residential setting, it is expected that there will be many instances of a second fitting coming a short distance from a previous fitting (0–12 in.). The team collected data to understand the flow characteristics through multiple elbow configurations.

Flow through an elbow exhibits a nonuniform pressure profile, such that there is a low-pressure region on the inside radius of the elbow and for a short distance after the elbow. This flow separation effect might be the primary cause of any interactions between elbows. The azimuth angle of the next fitting might also influence the total flow resistance. An “S” shape with the net flow continuing in a parallel path might exhibit different behavior than a “U” shape in which the flow undergoes a 180-degree direction change.

Data collected in this phase are also used by the building simulations. The AFN model component of EnergyPlus can solve the air movements in a structure based on node pressure differences and linkage component parameters. These component parameters include duct diameter, roughness, and U-value.

The primary concern with shrinking duct size is the increased fan energy necessary to move air through the pipe diameter. The Darcy-Weisbach equation can be represented in a way (Eq. 3) that shows that the flow resistance increases according to the radius to the power of 5. This means that small changes in duct radius can have a significant impact on overall flow resistance when supplying the same volumetric flow rate.

$$\Delta p = f\frac{\ell p(Q)^2}{4\pi^2 r^5} \tag{3}$$

where $f$ is the friction factor, $l$ is the duct length, $r$ is the duct radius, $\rho$ is the fluid density, and $Q$ is the fluid flow rate.

Using this equation, the pressure drop has been calculated per foot for a smooth pipe of several inner diameters, as shown in Figure 3. The dramatic increase in flow resistance as the pipe diameter decreases is evident. Even a ¼-in. change in pipe diameter can significantly impact the pressure drop. The optimal small-diameter pipe for residential ductwork will have the thinnest wall possible, be large enough to minimize flow loss, and yet be small enough to fit easily in the interior wall cavities (i.e., <3.5-in. outer diameter).

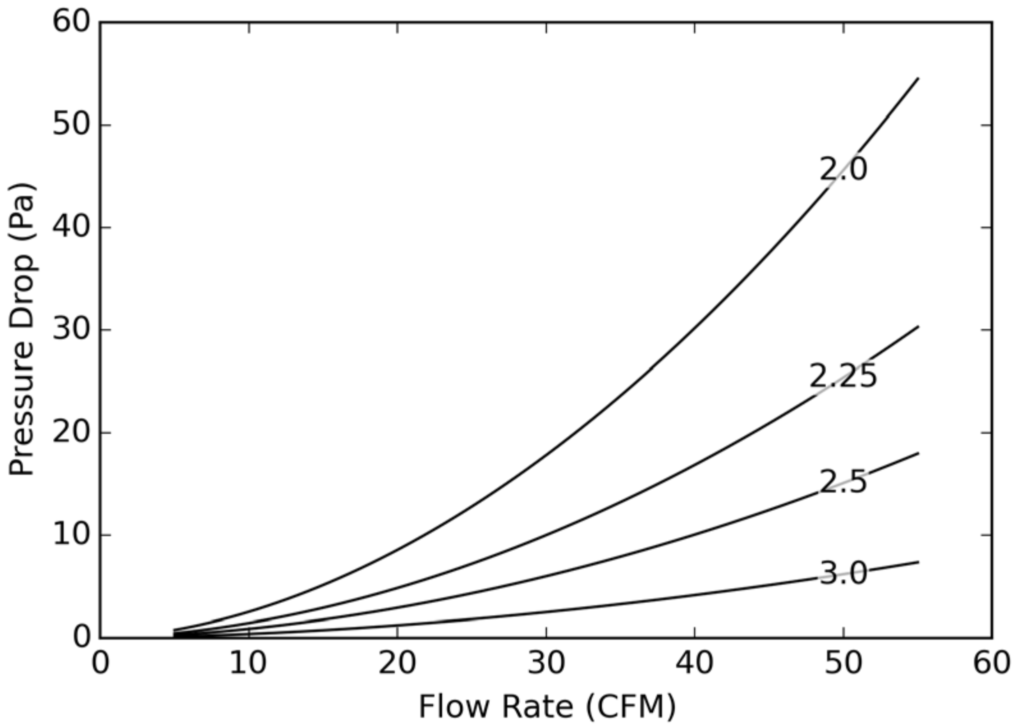


**Figure 3. Duct resistance relationships for various duct diameters**

Although understanding the fan energy impact of using the home-run system was not a primary consideration of this report, it might be a concern for the eventual commercialization and adoption of the technology. By utilizing a compact duct layout and smooth ducts of a medium-small diameter (2.5–3.0 in.), any increase in static pressure and fan energy will be minimized. The design method assumes 87 Ps (0.35-in. water column) of available static pressure to the duct system, which can be achieved by electronically commutated motor-driven AHU fans. This value is greater than that for which conventional duct systems are designed but less than that for current small-diameter duct systems. Measured data, discussed in the Performance Evaluation section of this report (Section 4), showed that for an installed 2-in.-diameter duct system, the fan power draw was 0.33 W/CFM (86 W/259 CFM) at its highest speed setting.

Another consideration in lowering the total external pressure in the proposed technology is in minimizing the return duct length and losses. By putting the air handling equipment in or near conditioned space, it is anticipated that little to no return ductwork will be necessary, besides a filter and grille assembly.

Figure 4 shows airflow-versus-pressure drop measurements compared to calculated curves, with two different duct roughness values. The measured data align well with a very low (approximately 0) duct roughness value.

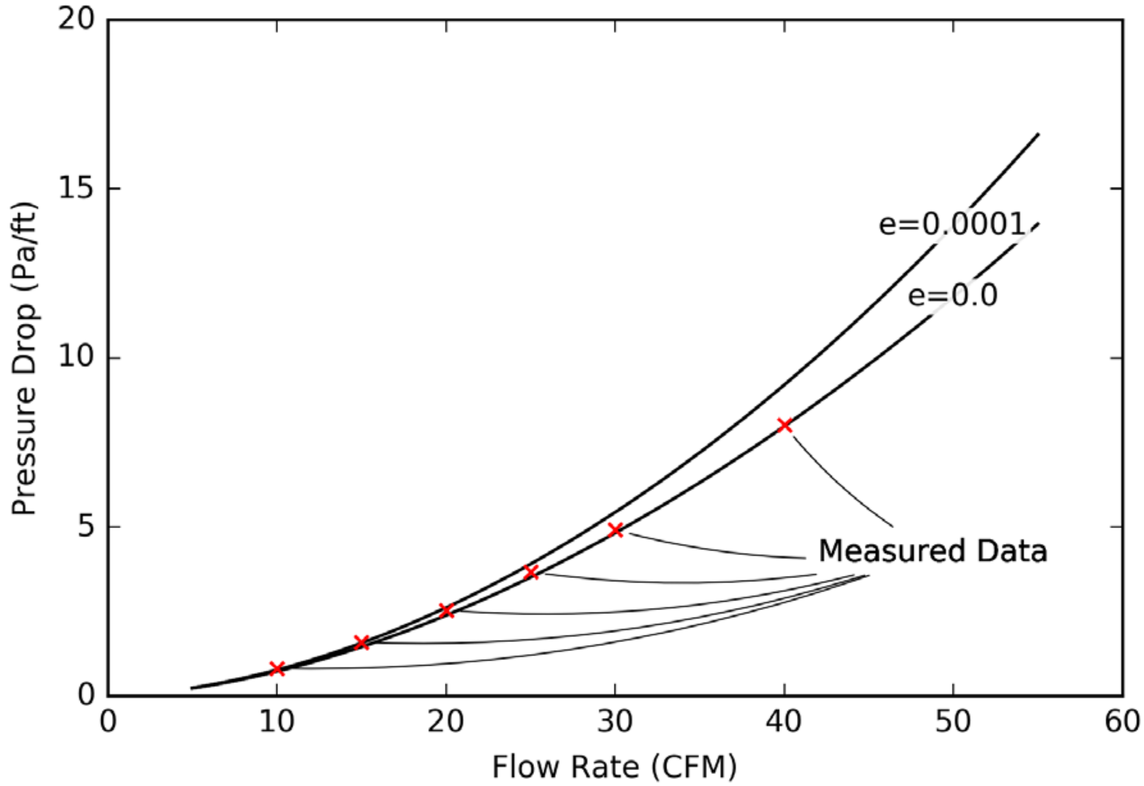


**Figure 4. Theoretical and predicted airflow-versus-static pressure drop, 2-in. round pipe**

### *2.2.2 Experimental Testing Procedure*

The team used ASHRAE Standard 120 as a technical basis for conducting lab tests; however, we did not follow the procedure exactly. This standard specifies procedures for accurately measuring flow resistance in ductwork and fittings. ASHRAE Standard 120 outlines a specific set of lab testing procedures as well as analysis and correction factors/methods. Standard 120 specifies that the test velocity should be between 9 and 36 m/s (1,772–7,087 fpm), or 6 m/s for a branch. The minimum pressure loss should be 75 Pa or the pressure resulting from a mean velocity of 9 m/s (6 m/s [1,181 fpm] in a branch), whichever is smaller. Achieving this pressure drop is not practical for the smooth and relatively low-airflow velocities in question. An additional limiting factor is the decrease in accuracy for the test fan (duct testing fan) as the back pressure exceeds 100 Pa.

Testing included lengths of straight duct, single elbows, and multiple elbow combinations. The team tested 30 unique combinations of distance and azimuth. Distances of 0, 1, 2, 4, 8, and 12 in. were tested at 0, 45, 90, 135, 180-degrees azimuth. Figure 5 shows the Azimuth orientation for two elbow tests, with a single duct rotated through three orientations.

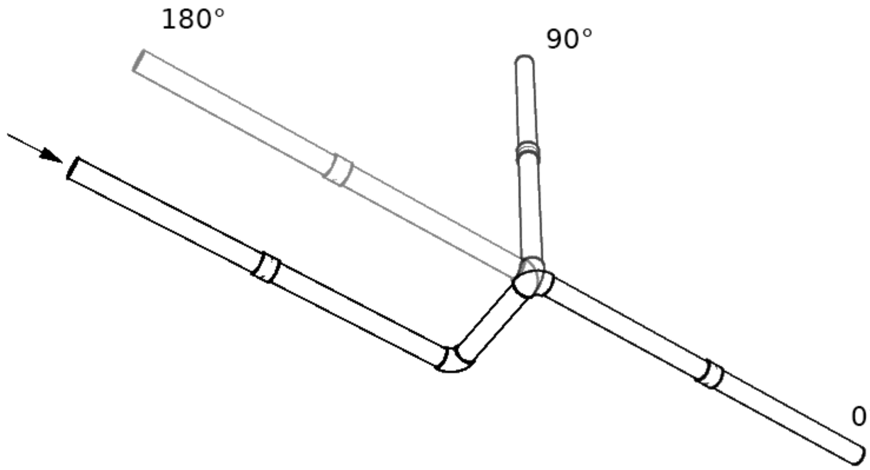


**Figure 5. Azimuth orientation of two 2-in. PVC elbows**

The measurements shown in Table 2 indicate the type of measurement, sensor used, and accuracy. Ambient conditions (temperature, relative humidity, barometric pressure) were measured at the start of testing for each component and assumed to remain constant throughout the duration of the test.

**Table 2. Summary of Measurement Devices and Accuracy**

| Measurement | Sensor | Accuracy |
|---|---|---|
| Ambient air temperature | Fluke 975 | ±0.5°C |
| Ambient air humidity | Fluke 975 | ±3% relative humidity |
| Ambient air barometric pressure | Fluke 975 | ±3% |
| Air temperature in duct | Type T Thermocouple | ±0.5°C |
| Air volumetric flow rate | TEC Duct Blaster and DG-700 | ±3% (5-s average) |
| Static pressure at duct blaster exit | DG-700 | ±1% (5-s average) |
| Static pressure at entrance of test section | DG-700 | ±1% (5-saverage) |
| Static pressure at exit of test section | DG-700 | ±1% (5-s average) |

Testing was conducted in a large, open laboratory space using semi-conditioned ambient air (70°–80°F).[4] The supply fan (Minneapolis Duct Blaster) was connected in series to a reducer and then to duct test sections. To reduce the duct diameter from the 10-in. discharge to the 2-in. diameter of the smallest duct, a steel transition section was fabricated. The transition was designed such that the angle between its wall and the axis parallel to the duct was 7.5° to comply with ASHRAE Standard 120. Figure 6 shows a diagram of the testing apparatus.

[4] Air density was calculated at the measured testing air temperature and found to vary much less than the accuracy of the testing equipment. Measured values for flow rate were not modified beyond the assumed standard value.

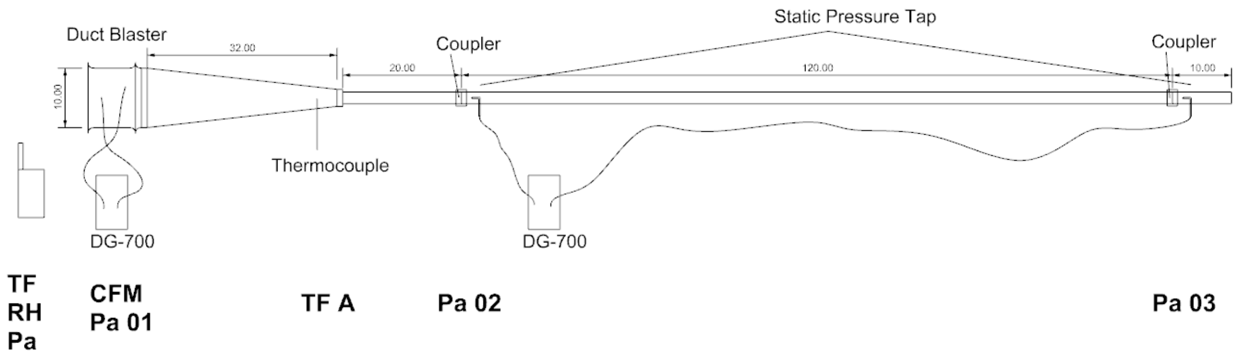


**Figure 6. Diagram of testing apparatus**

Figure 7 shows the testing apparatus with a single 10-ft section of 2-in. PVC pipe attached. Figure 8 shows smoke testing of the pressure tap to ensure no leakage from the duct.


**Figure 7. Example test setup with duct blaster connected to a PVC pipe. The conical steel reducer is also shown.**

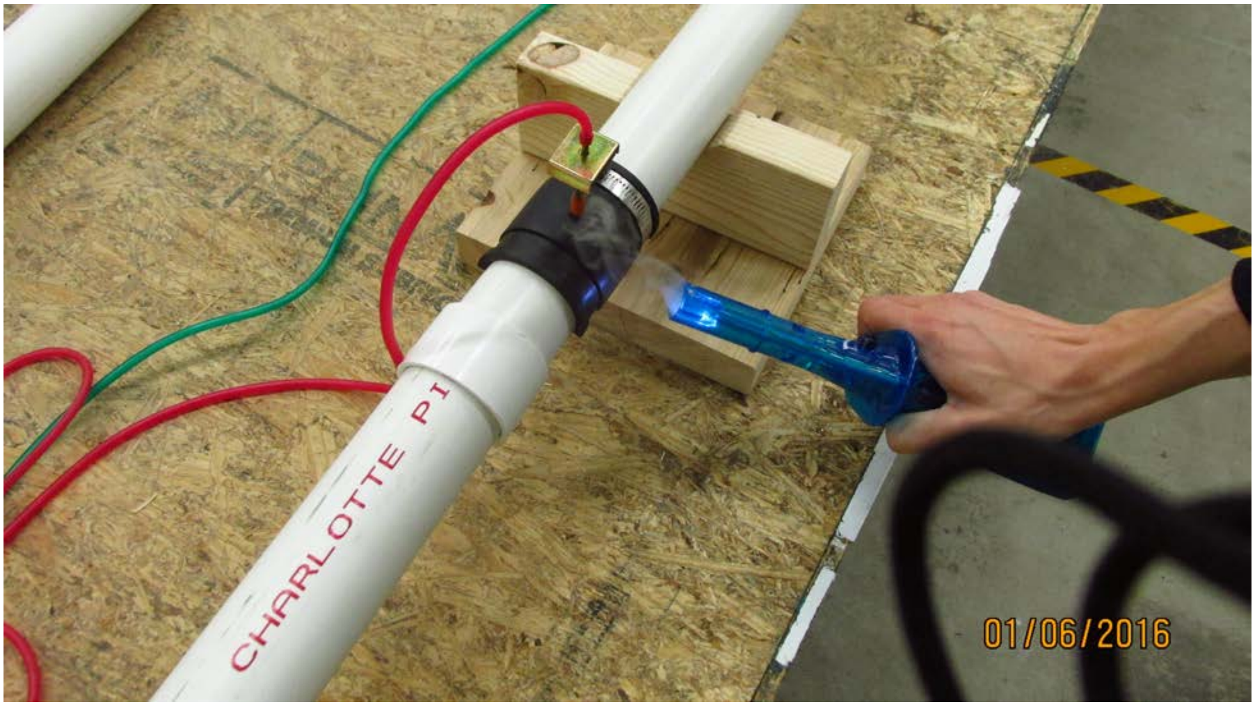


**Figure 8. Static pressure tap shown with rubber saddle mount. Smoke is being used to test for air leakage.**

To measure the pressure drop through an elbow, it is necessary to have some length of straight ductwork before and after the elbow for the airflow to develop for static pressure measurements. To simplify the process of subtracting the impact from this ductwork, two 5-ft sections of duct were used so that the pressure drop associated with 10 ft of duct can be simply subtracted from the measurement. This approach, using the difference in pressure drop, is shown in Figure 9.

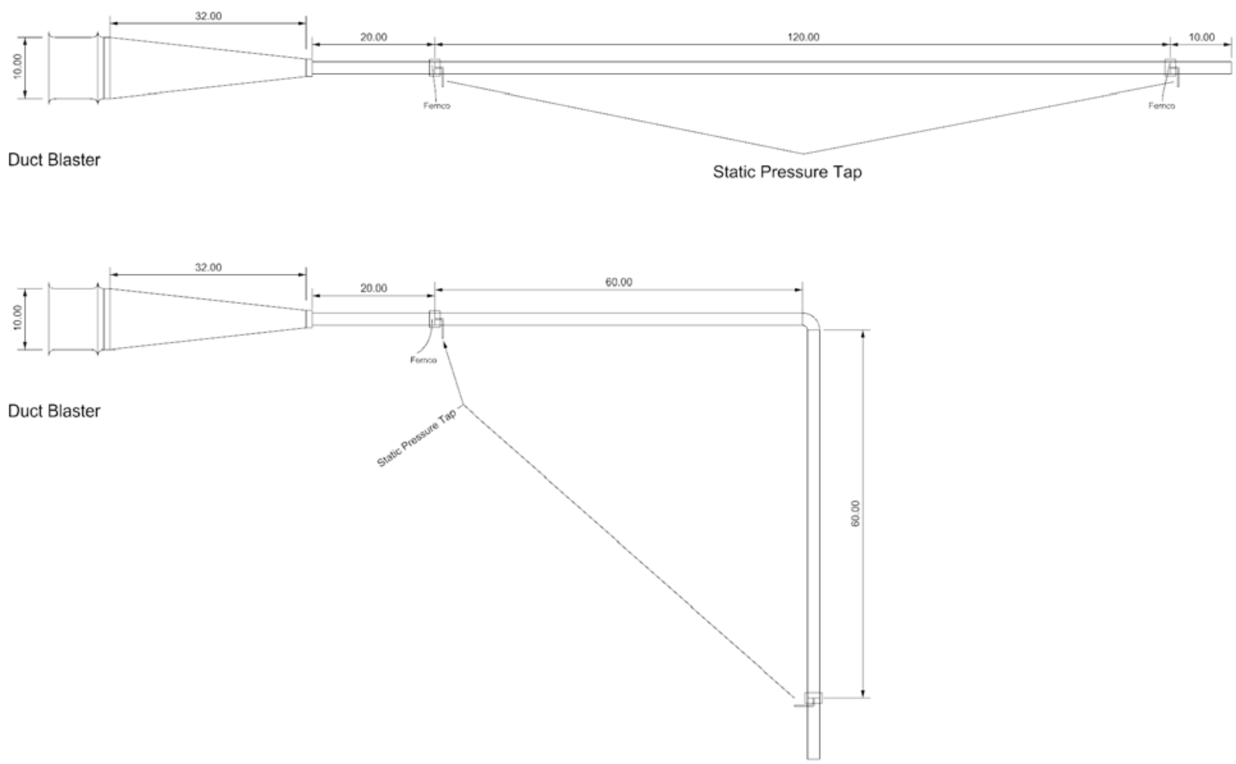


**Figure 9. Diagram showing elbow pressure drop measurement**

The team also studied temperature loss along the length of duct sections. This information was used in the simulation phase of the project. Additionally, this information can be used to compare thermal losses for different duct diameters and insulation scenarios.

The simulation requires an average duct U-value, which includes the effects of conduction and convection to be input as a parameter. To measure this, the team heated the inlet air and measured the temperature loss along a length of duct. The inlet air was heated by switching on two to four 300-watt electric heaters while the inlet air was observed until it reached a steady value within 5°F of the target value. It was assumed that the air was well mixed after the fan. The target value was 113°F. Once the desired inlet temperature is reached, the operator would ensure that the flow rate and inlet temperature remain constant until the outlet temperature stabilizes. Given these steady-state conditions, the overall U-value could be calculated. Figure 10 shows the air mixing box and portable space heaters. The duct testing fan drew all its airflow through this box.

The heated air would affect the accuracy of the duct blaster flow measurement because of a change in air density. At 113°F the duct blaster accuracy would be impacted by up to 4%.

The team supplemented the pressure loss testing equipment with a thermocouple inserted at the inlet and outlet of each duct test section. The thermocouples were attached to a Campbell Scientific data logger and had an accuracy of ±0.5°C.


**Figure 10. Mixing box with portable space heaters**

### *2.2.3 Analysis*

Measurements for each test were analyzed using a spreadsheet program. After recording measurements on a physical media, values were entered onto a template. Calculations were then performed to relate pressure to volumetric flow rate. The team chose to relate pressure to volumetric flow rate instead of air velocity because volumetric flow rate is the output variable desired for the design methodology.

Flow and pressure can be related using the following equation (Eq. 4):

$$\Delta P = Cq^n \tag{4}$$

where $\Delta P$ is the pressure drop per unit length, $C$ is the flow coefficient, $q$ is the volumetric flow rate, and $n$ is the flow exponent.

Measured data were fit to this equation using Microsoft Excel's built-in trend-line functionality to determine the values for $C$ and $n$. Each material and diameter has unique $C$ and $n$ values.

An equivalent length was calculated for each elbow fitting tested. The equivalent length was calculated by iteratively multiplying the pressure drop per foot of straight duct by a length (Eq. 5) until the pressure drop matched the value measured for only the elbow:

$$\Delta p_e = L_e * \Delta p_{/ft} \tag{5}$$

The total root mean square error between the measured pressure drop and the equivalent pressure drop was minimized for all flow rates. This resulted in a single equivalent length that was the best fit for each flow rate.

Duct average conductance values for use in EnergyPlus AFN modeling were calculated using the following equation (Eq. 6):

$$U = -\frac{\dot{m} * Cp}{A} * \ln\left(\frac{T_o - T_a}{T_i - T_a}\right) \tag{6}$$

where $U$ is the duct's average thermal conductance, $m$ is the mass flow rate of air, $Cp$ is the heat capacity of air, $A$ is the duct's surface area, $T_o$ is the outlet temperature, $T_a$ is the ambient air temperature, and $T_i$ is the inlet air temperature.

This equation is from the EnergyPlus Engineering Reference documentation, Eq. 13.220. In the original documentation, the equation is arranged to solve for $T_o$. The equation has been rearranged to solve for $U$ based on lab-measured input values. U-values were calculated at four different flow rates (15, 20, 25, 30 CFM) and then averaged. These rates were chosen because they are expected for the duct during the simulation exercise.

#### *2.2.4 Measurements and Discussion*

Figure 11 shows all the tested materials. The ducts are labeled numbers 1–10, and the two insulation types that were used are labeled numbers 11 and 12. For this work, PVC was the primary material under consideration; however, 3-in. flexible duct provides a code-accepted small-diameter material. Other materials were tested as references and for exploration of possible solutions.

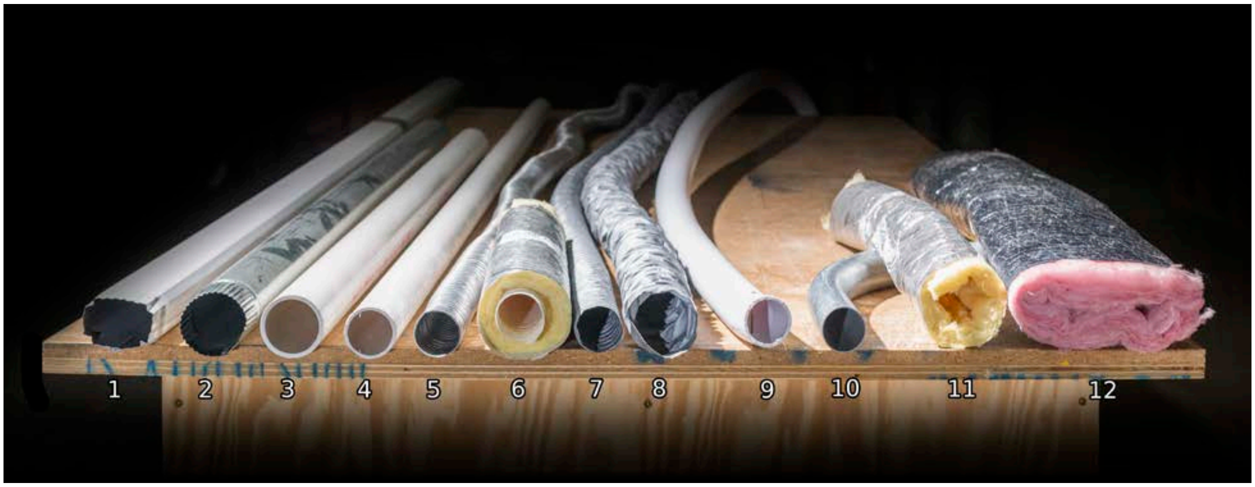


**Figure 11. Duct materials and insulation.**

1: down spout; 2: snap lock; 3: 2.5 in. PVC; 4: 2-in. PVC; 5: aluminum flex; 6: nylon fabric; 7: 3-in. flexible duct 2 in.; 8: 3-in flexible duct 3 in.; 9: flexible PVC; 10: steel conduit; 11: R-4.2; 12: R-6.0

Table 3 presents a summary of all tested materials, including parameters and calculated flow properties. Flow data have been normalized by the length of the ductwork; as a result, the reported flow coefficients are small numbers. Because the rigid PVC was the primary material under consideration, it was tested at multiple lengths.

**Table 3. Summary of Flow Properties of Materials Tested**

| Nominal Diameter | Material | Inner Diameter | Outer Diameter | Lengths Tested[a] | Flow Exponent | Flow Coefficient |
|---|---|---|---|---|---|---|
| 2 | PVC | 2.067 | 2.375 | 10 $ft_9$, 20 $ft_9$, 30 $ft_3$, 40 $ft_2$ | 1.702 | .01146 |
| 2.5 | PVC | 2.469 | 2.875 | 10 $ft_6$, 20 $ft_1$, 30 $ft_1$, 40 $ft_1$ | 1.706 | .00556 |
| 2 | 3-in. flexible duct | 2.065 | 2.185 | 10 $ft_2$ | 1.975 | .00951 |
| 3 | 3-in. flexible duct | 3.069 | 3.075 | 10 ft | 2.0345 | .00105 |
| 2 | Nylon fabric | N/A | N/A | 14 $ft_3$ | 1.834 | .0196 |
| 2 | Alum. flex | 2.035 | 2.25 | 24 $ft_1$ | 1.804 | .0097 |
| 2 | Steel conduit | 2.063 | 2.22 | 10 $ft_3$ | 1.686 | .0118 |
| 2x3 | Down spout | N/A | N/A | 10 $ft_2$ | 1.697 | .0023 |
| 3 | Snap lock | 3.015 | 3.155 | 10 $ft_3$ | 1.737 | .0018 |
| 2 | Flexible PVC | 2.19 | 2.35 | 10 $ft_5$, 20 $ft_5$ | 1.684 | .0126 |

[a] Subscripts denote number of times length was tested.

For each material, the flow exponent represents the rate at which the pressure increase increases. An exponent of 1 would represent a linear increase. Rough materials—i.e., flexible ductwork—tend to have higher exponents, which means that they are more susceptible to pressure drop at higher flow rates. The smoother duct materials respond more linearly to increased airflow.

The flow coefficient is a scale factor on the pressure loss. The coefficient for 2.5-in. PVC is approximately half that of 2-in. PVC, but both have similar exponents. This means that the relative shape of each curve is similar, whereas the 2.5-in. PVC pipe has half the pressure drop.

Figure 12 shows the raw pressure drop measurements for each material. There is an obvious correlation between material diameter and pressure drop. The worst-performing material was the 2-in. flexible nylon duct, whereas the best performing material was 3-in. steel snap lock. The 3-in. flexible duct when pulled tight performed close to the snap lock, but the small amount of roughness caused by the inner-wire helix caused additional pressure loss.

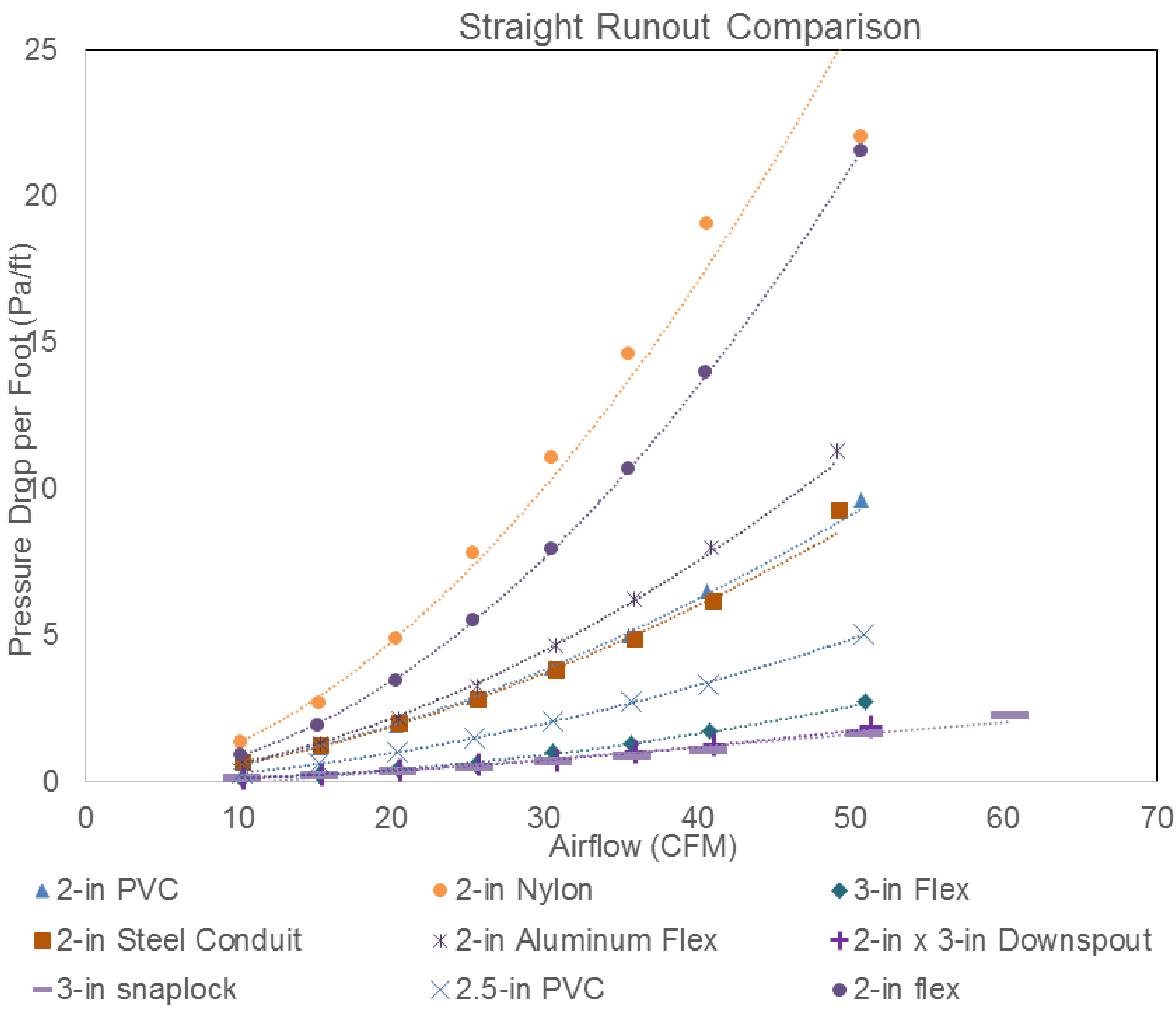


**Figure 12. Straight runout comparison**

To show the impact that length has on measured pressure drop, Figure 13 shows four tests of 2-ft PVC. Measurements from lengths of 10 ft, 20 ft, 30 ft, and 40 ft are shown. Differences in measurement are likely because of the impact increased back pressure has on the accuracy of the flow meter and fan (duct testing fan). The back pressure values for the 20-ft, 30-ft, and 40-ft tests were more than 100 Pa, which is beyond the recommendation of the fan manufacturer. The accuracy is unknown for these measurements. For the purposes of this analysis, measurements from the 10-ft test were used.

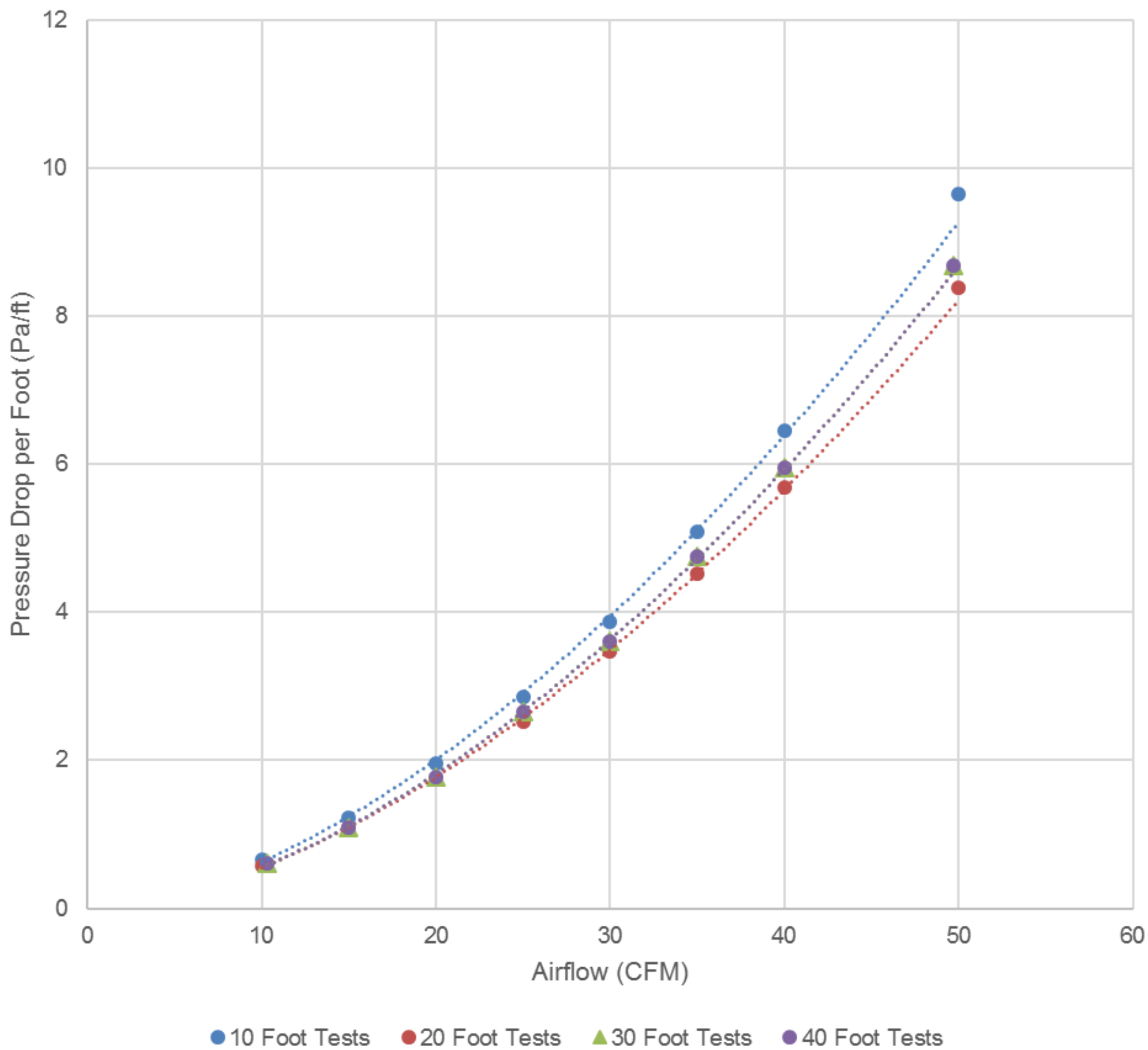


**Figure 13. Two-inch PVC pressure drop per foot. Different lengths are compared.**

Figure 14 presents measurements from nine tests of 2-in.-diameter, 10-ft-long pipes. These values show the repeatability of the testing. At 40 CFM, the average pressure drop was 64.5 Pa, and the standard deviation of the measurements was 1.3 Pa. This is near the expected accuracy of 1.29 Pa (+2% * 64.5) for the pressure measurement. An additional error of +/-3% is introduced in the airflow measurement.

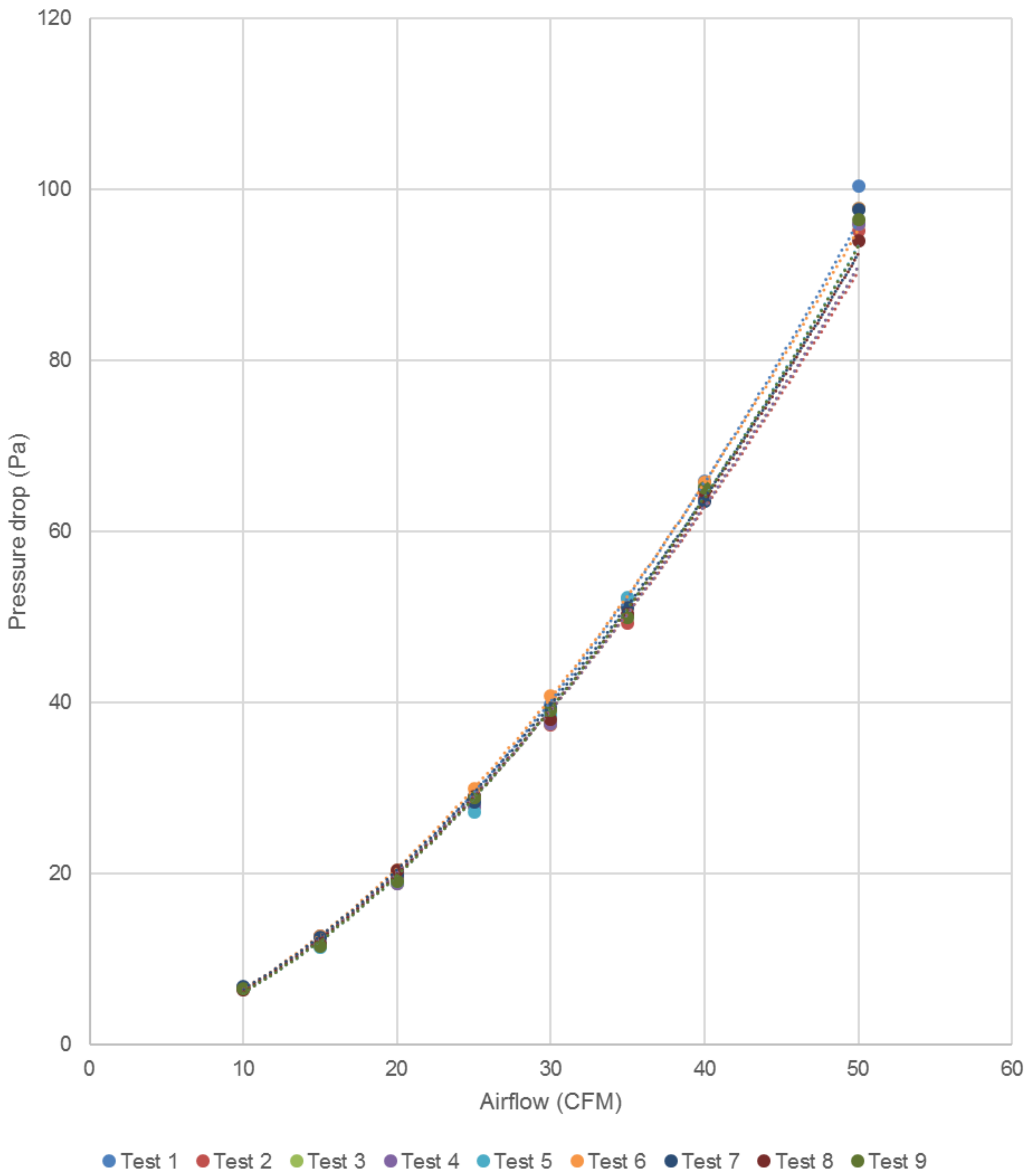


**Figure 14. Two-inch PVC of 10-ft length. Nine tests were compared for repeatability.**

Table 4 presents results of the thermal loss testing. The impact of adding insulation is apparent in the reduced overall U-value. The smaller ducts (<=2.5 in.) used an R-4.2 jacket, whereas the larger ducts used an R-6 jacket. Tests were conducted with the larger R-6 jacket on smaller ducts; however, the insulation was not snug, and the results have been omitted.

**Table 4. Summary of Thermal Properties of Materials Tested**

| Nominal Diameter | Material | Inner Diameter | Outer Diameter | Insulation R | U-Value* (BTU/h*ft$^2$) |
|---|---|---|---|---|---|
| 2 | PVC | 2.067 | 2.375 | - | .992 |
| 2 | PVC | 2.067 | 2.375 | 4.2 | .243 |
| 2.5 | PVC | 2.469 | 2.875 | - | 1.01 |
| 2.5 | PVC | 2.469 | 2.875 | 6 | .379 |
| 2 | St. conduit | 2.063 | 2.22 | - | 1.06 |
| 2 | St. conduit | 2.063 | 2.22 | 4.2 | .325 |
| 2x3 | Downspout | N/A | N/A | - | .802 |
| 2x3 | Downspout | N/A | N/A | 6 | .141 |
| 3 | Snap lock | 3.015 | 3.155 | - | .884 |
| 3 | Snap lock | 3.015 | 3.155 | 6 | .281 |
| 3 | 3-in. flexible duct | 3.069 | 3.075 | - | 1.38 |
| 3 | 3-in. flexible duct | 3.069 | 3.075 | 6 | .129 |
| 2 | Flexible PVC | 2.19 | 2.35 | - | 1.02 |

* A propagation of uncertainty was performed in Engineering Equation Solver v. 9. The uncertainty for the 2-in. PVC pipe was ±0.184 (BTU/h*ft$^2$)

Table 5 shows results from single-elbow testing. Fewer elbows were tested than duct types because only materials that were under serious consideration were tested. The 2-in. PVC 90° elbow had a 1-in. inner sweep and thus relatively low effective length. The 2.5-in. 90° elbow had no inner sweep and resulted in a much higher effective length. The nylon fabric duct elbow had a 6-in. sweep of uninterrupted duct material. Both the snap lock and 3-in. flexible duct used a standard jointed steel duct elbow. The 3-in. flexible duct showed a higher effective length, likely because of the less smooth transition because the flexible duct was connected to the rigid elbow.

**Table 5. Summary of Single 90° Elbow Test Results**

| Nominal Diameter | Material | Inner Diameter | Outer Diameter | Effective Length (ft) |
|---|---|---|---|---|
| 2 | PVC | 2.067 | 2.375 | 2.01 |
| 2.5 | PVC | 2.469 | 2.875 | 4.50 |
| 2 | Nylon fabric | N/A | N/A | 1.69 |
| 3 | Snap lock | 3.015 | 3.155 | 4.66 |
| 3 | 3-in. flexible duct | 3.069 | 3.075 | 9.32 |

Table 6 shows results from testing two sequential elbows. The average effective length is shown for each distance to understand the trend based on distance alone. Note that as two elbows move closer together, their total resistance is reduced. Also, note that the pressure loss associated with the spacing duct has been subtracted from these calculations—that is, if the distance is 8 in., then an additional 8 in. of duct loss was subtracted.

**Table 6. Summary of Two 90° Elbow Test Results**

| Nominal Diameter | Material | Distance (in.) | Angle | Average Equipment Length of One Elbow (ft) |
|---|---|---|---|---|
| 2 | PVC | 0 | 0,45,90,135,180 | 1.18 |
| 2 | PVC | 1 | 0,45,90,135,180 | 1.15 |
| 2 | PVC | 2 | 0,45,90,135,180 | 1.15 |
| 2 | PVC | 4 | 0,45,90,135,180 | 1.02 |
| 2 | PVC | 8 | 0,45,90,135,180 | 1.05 |
| 2 | PVC | 12 | 0,45,90,135,180 | 1.00 |

When the two elbows were rotated such that the second duct was at 0° relative to the first elbow, creating a U shape, the equivalent length was minimized. Rotating the second duct at 180° relative to the first elbow, creating an S shape, increased the equivalent length. Figure 15 shows the results of these measurements. The overall effect was minimal, however, relative to the total pressure drop in a duct system. The team decided not to account for these unique cases in the design methodology.

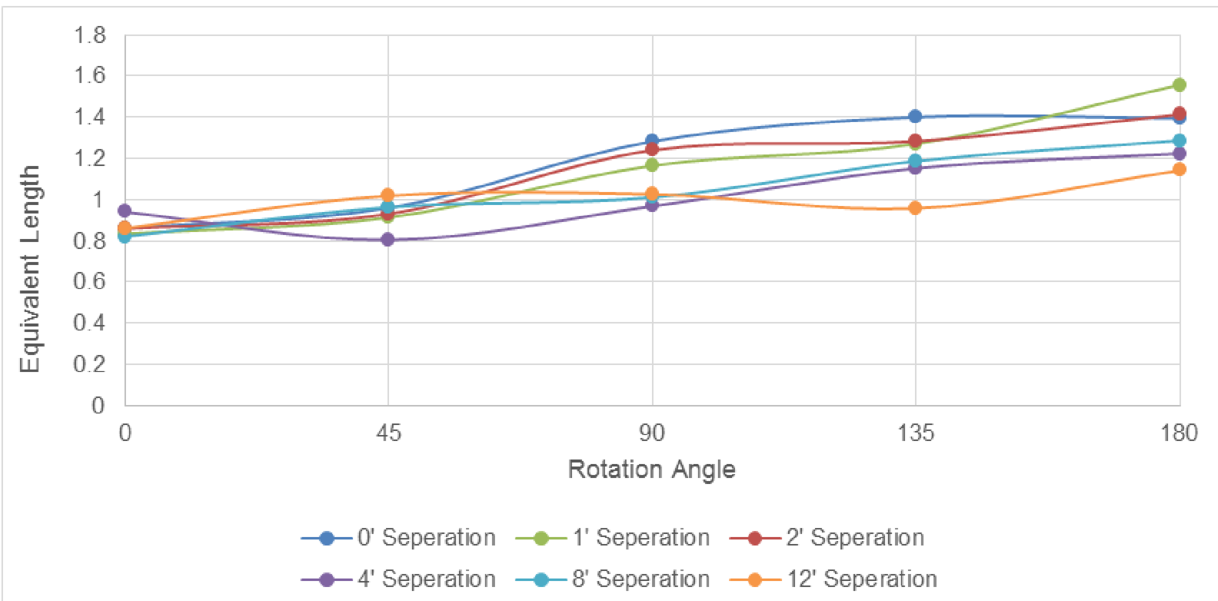


**Figure 15. Equivalent length of two 2-in. PVC elbows**

In addition to testing the duct runouts, the team measured a sample manifold box to determine if the pressure drop associated with the flow through the manifold and into the ducts was significant. A 14-in. by 20-in. by 16-in. box was constructed with eight 2.5-in. holes. A small, 3-in. piece of duct was attached to each hole to provide the inlet region for a duct. The box was then pressurized with a duct blaster, and measurements were taken at various flow rates. At 343 CFM, the pressure drop was 0.1-in. water column, lower than what might be expected from an air filter. This pressure loss highly depends on the shape of the duct inlet. Using a swept inlet, it is anticipated that the pressure drop could be lowered even further. Similar in concept to the PnP duct box, previous research on flexible-duct splitter boxes showed a 0.055-in. water column loss associated with a box with four equally sized outlets when 400 CFM was moved through the box (Beach and Prahl 2013).

## 2.3 Design Method Candidates

Current residential duct design practices are specified in ACCA *Manual D* (Rutkowski 2014). This approach requires the user to have access to parameter data for a wide variety of fittings and carefully tabulate each fitting and piece in each duct runout. The longest runout is then used to determine the total effective length of the duct system. Using the total effective length, a friction rate is calculated. This friction rate is then used to size each airway (with different sizing for round, rectangular, and oval ducts and based on the specific material, sheet metal, duct board, or flexible ductwork). The designer must also consider the total available static pressure or the potential that exists to move air though the duct system after the loss associated with each other component has been removed. The proposed design methodology greatly simplifies this process.

With the goal of picking the simplest design method that will deliver the needed comfort, the team developed the following four design methods for evaluation. Each one increases in complexity and precision.

- **Design Method 1:** Each duct is assumed to get the same airflow, regardless of length. A nominal airflow through each duct is assumed, based on the total system airflow. The airflow needed by each zone is then divided by the nominal airflow and rounded up to determine the number of ducts. This method is the easiest; however, it could result in insufficient airflow and reduced comfort.
- **Design Method 2:** This is similar to Design Method 1; however, a length-based airflow correction factor is applied to the shorter and longer ducts. Measured data indicated the following values for 2.5-in. PVC ducts: 5–15 ft.: 1.5 times; 15–25 ft: 1 time; 25–35 ft: 0.8 time. These are the nominal airflows from Design Method 1 multiplied by the relevant length-based correction factor (1.5, 1, or 0.8). These correction factors were derived by considering the average reduction in flow for a 5–15-ft increase for a 25–35-ft duct compared to a 20-ft baseline duct.
- **Design Method 3:** Based on the available static pressure, the actual airflow through each duct is calculated using a spreadsheet tool. Duct lengths are estimated based on house plans and a rough layout. This design approach was ultimately selected for the PnP system. A detailed discussion of the calculations is included in the Design Methodology Development section (Section 2.1) of this report.
- **Design Method 4:** This extends Design Method 3 by also attempting to account for the temperature loss along the length of the duct. This has the net result of increasing the number of ducts to some spaces.

Ultimately, Design Method 3 was selected to provide the best balance between simplicity and accuracy. The results of the simulation effort were included in this decision; these are detailed in the results section (Section 4.4).

Because the design method was assumed to use a spreadsheet tool to calculate the number of ducts, creating a pencil-and-paper design method was deemed unnecessary. Design methods 1 and 2 would have been simple enough to complete for the average design practitioner using hand calculations. Seeking to improve the accuracy of the prediction of the number of ducts, the team considered including the impact of temperature loss on the total number of predicted ducts. Design Method 4 estimated the average temperature loss per length of duct using an average UA value based on the inlet air temperature and environmental temperature. This method must make several assumptions about the location and orientation of the duct, number of ducts in a particular cavity, and the adjacent zones. Because the ductwork is in conditioned space, most energy lost along the length of the ductwork ends up in a conditioned zone. Predicting which zone the energy ends up in is not possible with a simple design tool. Given these factors, using a simple tool to predict the outlet temperature and the resulting impact on delivered energy is going to be marginally accurate at best. The results of the simulation effort also showed little improvement in comfort when accounting for temperature loss. Design Method 3 was chosen by the team as the optimal compromise between ease of use and accuracy.

The complete design method instructions can be found in Appendix B.

## 2.4 Range of Applicability

As a starting point for evaluating the range of applicability for the proposed system, the team performed a basic thermal energy delivery analysis. The purpose of this exercise is to understand at a high level whether the home-run duct system can deliver the needed energy, at a reasonable static pressure, to provide comfort in typical new construction homes. Calculated maximum delivered energy was compared to ACCA *Manual J* (Rutkowski 2006) load calculations for five typical residential designs as shown in Table 7.

**Table 7. Descriptions of Example Homes**

| House | Conditioned Ft$^2$ | Description |
|---|---|---|
| 1 | 876 | Single-story ranch house over an unconditioned basement |
| 2 | 1,124 | Middle unit of a three-story, town-house-style multifamily structure |
| 3 | 2,253 | Two-story house over a conditioned basement |
| 4 | 3,168 | Two-story house over a conditioned basement (Pittsburgh unoccupied lab house) |
| 5 | 4,157 | Large two-story house built on a slab |

Load calculations were performed at two different levels of enclosure codes (IECC 2009 and 2012), representative of current code levels enforced by many jurisdictions. Load calculations were also performed using weather data from cities located in three different climate zones: Orlando, Florida (Climate Zone 2), Fresno, California (Climate Zone 3), and Denver, Colorado (Climate Zone 5). These locations were selected to provide a variety of cooling and heating loads and relevance for production builders.

The following steps were used to determine the maximum possible energy delivered by the duct system:

1. **Calculate the airflow per duct.** Based on lab measurements, a flow-versus-pressure relationship has been established for various duct materials. Assuming an average total equivalent length of 30 ft for each duct, the airflow can be calculated for a given available static pressure. The total system airflow is highly sensitive to the duct lengths and available static pressure. For the purposes of this calculation, conservative values were selected that would be typical of those encountered in the real world. An optimized system could perform even better.
2. **Determine total system airflow.** The calculated airflow per duct is multiplied by the total number of ducts. For the purposes of this research, 16 has been selected as an upper limit on the target number of ducts for a single system. With any more, difficulties with installation begin to manifest, such as reaching ducts on the interior of the manifold and routing ducts into the ceiling or floor cavity immediately above the manifold.
3. **Calculate energy exchange.** The total system airflow is then multiplied by the energy transferred per CFM in both heating and cooling modes. The airflow factor used for heating, based on a 40°F temperature rise, was 0.0231 CFM/Btuh. The airflow factor used for cooling, based on a 30°F temperature drop and 0.85 SHR, was 0.0268 CFM/Btuh (320 CFM/t). The cooling airflow factor is somewhat beyond typical systems today and more in line with that used by small-diameter systems. These factors could be optimized to further improve the thermal capacity of the system.

Table 8 shows results of the maximum energy delivered by several duct diameters compared to the design heating and cooling load. Three different duct diameters are shown: 2-in. PVC, 2.5-in. PVC, and 3-in. flexible duct. The airflow per duct was calculated based on 0.3 in. of available static pressure in the manifold and a duct length of 30 ft. This static pressure value is slightly higher than traditional ductwork design targets, but it could be achieved by an electronically commutated motor-powered fan, with an adequately-sized return air system. Assuming a lower static pressure would result in lower airflow and less potential market applicability. Future work could optimize the static pressure and duct configuration to maximize the market applicability of the home-run duct system.

Presented results show that 2.5-in. smooth ductwork could condition a 2,252 $ft^2$ home in climate zones 2–5. Even larger homes could be conditioned using 3.0-in. ductwork. Smaller homes, less than 1,200 $ft^2$, or very low-load homes built to certification standards of the Passive House Institute US could be conditioned using 2-in. smooth ductwork.

**Table 8. Example Ranges of Applicability[a]**

| House | Ft² | Climate | Code | Load-H | Load-C | 2.0 in. H | 2.0 in. C | 2.5 in. H | 2.5 in. C | 3.0 in. H | 3.0 in. C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| House 1 | 876 | Climate Zone 2 | 2009 | 12,280 | 13,922 | Green | Green | Green | Green | Green | Green |
| | | | 2012 | 8,095 | 10,361 | Green | Green | Green | Green | Green | Green |
| | | Climate Zone 3 | 2009 | 12,474 | 11,477 | Green | Green | Green | Green | Green | Green |
| | | | 2012 | 9,083 | 9,681 | Green | Green | Green | Green | Green | Green |
| | | Climate Zone 5 | 2009 | 14,200 | 10,397 | Green | Green | Green | Green | Green | Green |
| | | | 2012 | 10,964 | 9,412 | Green | Green | Green | Green | Green | Green |
| House 2 | 1,124 | Climate Zone 2 | 2009 | 10,487 | 14,846 | Green | Green | Green | Green | Green | Green |
| | | | 2012 | 6,064 | 11,527 | Green | Green | Green | Green | Green | Green |
| | | Climate Zone 3 | 2009 | 9,674 | 14,594 | Green | Green | Green | Green | Green | Green |
| | | | 2012 | 6,428 | 9,696 | Green | Green | Green | Green | Green | Green |
| | | Climate Zone 5 | 2009 | 13,133 | 12,471 | Green | Green | Green | Green | Green | Green |
| | | | 2012 | 10,139 | 11,744 | Green | Green | Green | Green | Green | Green |
| House 3 | 2,252 | Climate Zone 2 | 2009 | 20,618 | 21,709 | Red | Red | Green | Green | Green | Green |
| | | | 2012 | 12,837 | 16,811 | Green | Red | Green | Green | Green | Green |
| | | Climate Zone 3 | 2009 | 19,130 | 20,580 | Red | Red | Green | Green | Green | Green |
| | | | 2012 | 13,559 | 16,072 | Green | Red | Green | Green | Green | Green |
| | | Climate Zone 5 | 2009 | 27,491 | 17,782 | Red | Red | Red | Green | Green | Green |
| | | | 2012 | 22,552 | 16,894 | Red | Red | Green | Green | Green | Green |
| House 4 | 3,168 | Climate Zone 2 | 2009 | 27,253 | 18,207 | Red | Red | Red | Green | Green | Green |
| | | | 2012 | 17,010 | 13,359 | Green | Green | Green | Green | Green | Green |
| | | Climate Zone 3 | 2009 | 23,879 | 20,286 | Red | Red | Green | Green | Green | Green |
| | | | 2012 | 16,996 | 14,804 | Green | Green | Green | Green | Green | Green |
| | | Climate Zone 5 | 2009 | 34,739 | 11,687 | Red | Green | Red | Green | Green | Green |
| | | | 2012 | 28,250 | 10,533 | Red | Green | Red | Green | Green | Green |
| House 5 | 4,157 | Climate Zone 2 | 2009 | 42,608 | 43,232 | Red | Red | Red | Red | Green | Red |
| | | | 2012 | 27,952 | 33,423 | Red | Red | Red | Red | Green | Green |
| | | Climate Zone 3 | 2009 | 41,559 | 42,427 | Red | Red | Red | Red | Green | Red |
| | | | 2012 | 28,066 | 28,997 | Red | Red | Red | Red | Green | Green |
| | | Climate Zone 5 | 2009 | 56,440 | 26,148 | Red | Red | Red | Red | Red | Green |
| | | | 2012 | 46,416 | 22,339 | Red | Red | Red | Green | Red | Green |
| | | | | | Total Airflow (CFM) | 416 | | 624 | | 1,056 | |
| | | | | | Heating Btuh | 18,000 | | 27,000 | | 45,600 | |
| | | | | | Cooling Btuh | 15,500 | | 23,300 | | 39,300 | |

[a] Red indicates insufficient energy; green indicates sufficient energy.

As shown in this table, 2-in. PVC ductwork would provide sufficient airflow to condition smaller homes. Slightly larger, 2.5-in. PVC provides 50% more flow, and it could condition many medium-sized homes built to the IECC 2012. Using 3-in. flexible ductwork could condition even larger homes and introduce a wider variety of insulation levels.

Another consideration is the discharge velocity from each duct runout. With smaller diameter ducts, the discharge velocity can increase beyond acceptable levels. Commercially-available, small-diameter duct systems can reach discharge velocities of more than 2,000 ft/min. For each the example duct systems shown in Table 8, the discharge velocities are as follows: 2.0 in: 26 CFM, 1,200 ft/min; 2.5 in.: 39 CFM, 1,140 ft/min; 3.0 in.: 66 CFM, 1,350 ft/min.

Figure 16 shows the minimum duct diameters to keep the discharge velocity less than the specific values. For example, to keep the discharge velocity less than 1,500 ft/min. at 30 CFM would require a minimum duct diameter of approx. 1.8 in. ACCA *Manual T* (Rutkowski 2009b) recommends face velocities less than 700 ft/min for residential installations to keep the sound less than ambient values (<35 noise criteria). This recommendation, however, is for a diffuser-type terminal. It is expected that the velocity can be higher for simple round-type terminals with no elements in the airstream, as is standard practice for small-diameter duct systems that rely on the jet of air to mix the space. Generated sound is very dependent on the duct type and specific geometry of the diffuser. Measuring sound generated at the terminal was not part of this study; however, future work could identify the specific velocity threshold at which noise would be a concern.

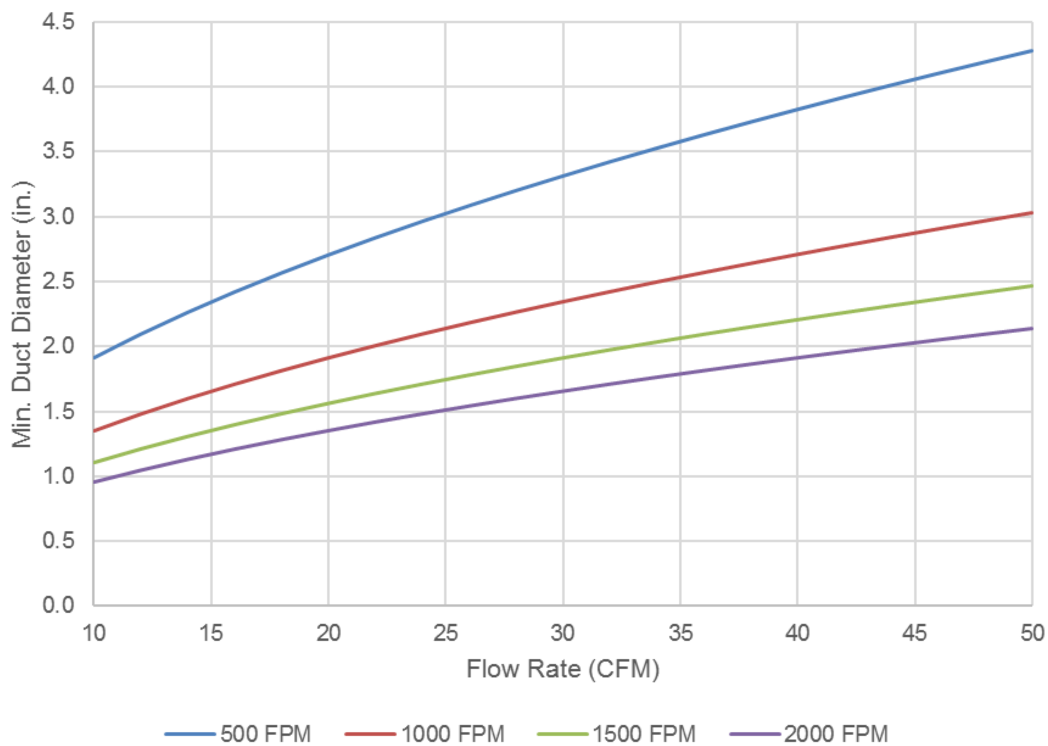


**Figure 16. Minimum duct diameters to keep discharge velocity less than various values**

# 3 Time and Motion Study and Cost Analysis

Cost is a key consideration for any new product introduced to the building market. To determine the labor and material cost of installing the PnP system compared to a traditional duct system, a time and motion study was conducted in a two-story mock-up of a town house. ACCA *Manual J* was used to calculate the heating and cooling loads for each zone of the house with an enclosure based on the IECC 2012 and Denver climate data. Based on these loads, a traditional rigid trunk-and-flex-duct branch duct system was designed using ACCA *Manual D*. The PnP design methodology was used to design a duct system for 2.5-in. and 2-in. semi-rigid pipe. The trunk-and-branch system required a finished ceiling chase for the trunk because the duct ran perpendicular to the direction of the floor structure. The 2.5-in. PnP system also used this chase as the ductwork and was not flexible enough to fit into the open-truss floor structure. The 2.0-in. PnP system was installed entirely in the existing floor structure and wall cavities (which is the intent of the PnP system).

Comparing the labor and material costs for the three systems showed a distinct advantage to the PnP system. Time-lapse photography was used to determine the length of time required for installing each system.

## 3.1 Test Mock-Up Construction

A two-story, wood-framed structure based on a production homebuilder's standard plan (Figure 17) was constructed in the IBACOS Innovation center. The building replicated the floor plan of an intermediate unit of a two-story town house and was comprised of 1,120 $ft^2$ of living space. The building was constructed with standard 2 x 4 walls and a floor system that consisted of ¾-in. OSB subflooring installed on 11 ¼-in.-deep parallel chord floor trusses. The ground floor plan was an open design with a kitchen at one end and the entry and living area at the other. A powder room was located near the base of the stairs that led to the second floor. A mechanical closet that houses the AHU was centrally located on the first floor. This location forced the duct system distribution to be installed in bulkheads or in the floor structure of the second floor. A bulkhead strategy for the traditional, larger (2.5-in. diameter) PnP system was chosen for ease of installation and simplicity of the duct routing. This strategy is very typical for this type of home.

The mechanical closet that housed the AHU was of typical construction for this type of building. A platform was installed approximately 2 ft from the floor upon which the unit sat. The area beneath the platform served as a field-constructed central return chase that fed directly into the bottom of the AHU.

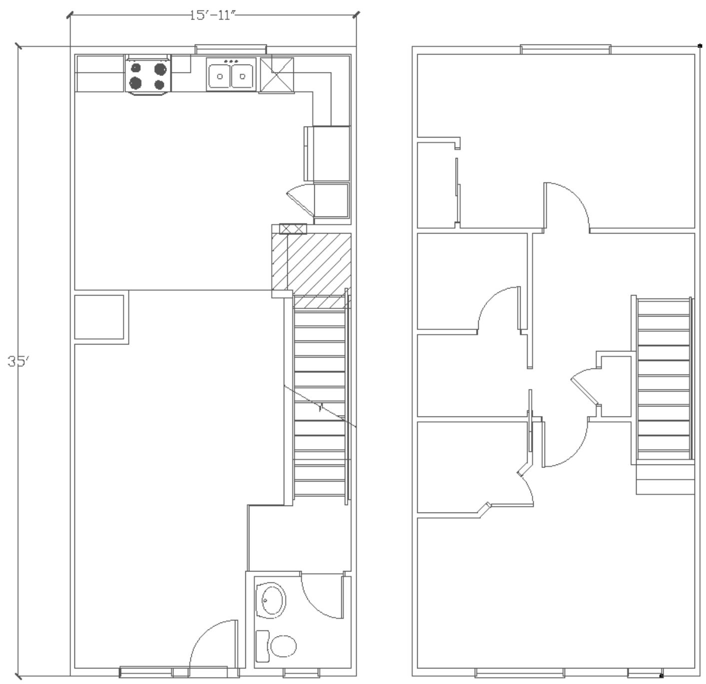


**Figure 17. Mock-up floor plan (not to scale)**

## 3.2 Time and Motion Study (Trunk-and-Branch System)

A *Manual D* duct design was created that identified the number of runs, sizes, and routing of the ductwork that would be necessary to properly condition the mock-up test home. From this design, a material list was created and ordered from a local HVAC supply company. The crew for this installation was two men who were familiar with both systems and all the components. Delivery and preliminary job setup were not accounted for in this study. The cost analysis is strictly based on the hard costs of the materials used and the direct labor time to perform the installation.

The sheet metal material for the trunk ducts were knock-down pieces that needed to be assembled on-site by the technician. Once the trunk ducts were assembled, all connections and seams were sealed with mastic or UL 181-rated foil tape. The two-man crew split the duties during the installation: one man was fabricating trunk ducts while the other was preparing the floor register cutouts for the duct boot locations in the individual rooms. The sheet metal boots were attached to the framing in their final positions. Following the completion of the trunk fabrication and the frame cutouts, the crew then began the installation by placing a 12.5-in. x 19-in. vertical supply plenum with two side takeoffs on top of the AHU (Figure 18). The fabricated sheet metal supply trunks were then attached to each of the side takeoffs. The trunk ducts ran along the corner area of the ceiling and exterior wall in a field-constructed bulkhead. Flexible duct collars were installed for each individual branch duct per the duct layout plan. Insulated flexible duct was then attached to the takeoff collars on the trunk and run to the boot locations (Figure 19). Like the trunk assembly, all connections for the flex duct were sealed as they would be in an actual home. The inner duct sleeve was secured down with ratchet-drawn cable ties and then wrapped with UL 181-rated foil tape. The outer insulation jacket was then pulled over the inner duct and secured in similar fashion with cable ties and the ratchet-tightening tool. All sheet metal was sealed with UL 181 mastic paste (Figure 20.)

**Figure 18. Riser plenum and side takeoff**

**Figure 19. Six-inch branch duct**

**Figure 20. Plenum sealing**

In general, the trunk-and-branch duct system installation was very straightforward and was accomplished by the two installers without any difficulties or issues. Figure 21 shows the design of the traditional trunk-and-branch system. Table 9 and Table 10 outline the materials and costs and the labor information gleaned from the actual time and motion study that was documented.

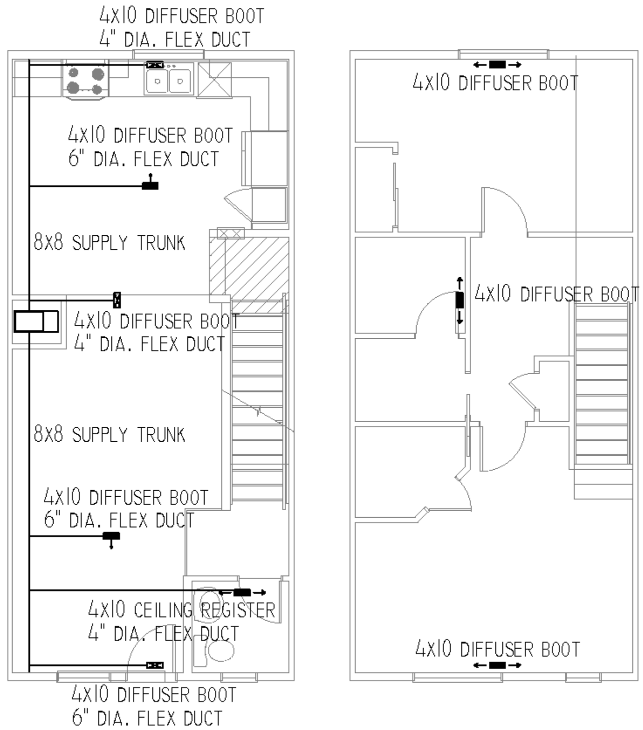


**Figure 21. Traditional trunk-and-branch system layout (not to scale)**

**Table 9. Trunk-and-Branch System Materials Cost**

| Material | Quantity | Cost Per Unit ($) | Total Cost ($) |
|---|---|---|---|
| Riser plenum | 1 | 36.48 | 36.48 |
| Junior canvas connector | 1 | 9.84 | 9.84 |
| 8-in. x 8-in. start collar | 2 | 5.65 | 11.30 |
| 6-in. insulated flex duct | 1 (25 ft) | 28.91 | 28.91 |
| 4-in. insulated flex duct | 1 (25 ft) | 25.34 | 25.34 |
| 6-in.-diameter 90 elbow | 3 | 2.36 | 7.08 |
| 4-in.-diameter 90 elbow | 3 | 2.53 | 7.59 |
| 6-in. start collar | 3 | 1.85 | 5.55 |
| 4-in. start collar | 3 | 1.85 | 5.55 |
| 6-in. register boot end, center | 3 | 6.39 | 19.17 |
| 4-in. register boot end, center | 1 | 7.66 | 7.66 |
| 4-in. register boot elbow | 2 | 7.57 | 15.14 |
| Snap-lock duct 8 in. x 8 in. | 35 ft | | 144.24 |
| End cap 8 in. x 8 in. | 2 | 3.01 | 6.02 |
| Duct mastic | 1 gal | 13.91 | 13.91 |
| Cable ties | 1 pkg. | 16.56 | 16.56 |
| Slip and drives | 1 pkg. | 25 | 25 |
| Sheet metal screws | 1 pkg. | 34.2 | 34.2 |
| **TOTAL** | | | **419.54** |

**Table 10. Trunk-and-Branch System Labor Cost**

| Description | Time/Person (min) | Labor Rate $/person.h[a] | Crew Size | Assembly Labor Cost ($) |
|---|---|---|---|---|
| Fabricate supply plenum and seal with mastic | 21 | 33.35 | 1 | 11.67 |
| Lay out and cut floor registers | 39 | 33.35 | 1 | 21.68 |
| Fabricate trunk ducts | 16 | 33.35 | 1 | 8.89 |
| Install trunk collars to supply plenum and seal with mastic | 29 | 33.35 | 1 | 16.12 |
| Install floor boots and seal to subfloor with tape and mastic | 49 | 33.35 | 1 | 27.24 |
| Seal trunk ducts with mastic | 15 | 33.35 | 1 | 8.34 |
| Install supply plenum onto AHU | 19 | 33.35 | 2 | 21.12 |
| Lay out and cut trunk locations through closet sidewalls | 12 | 33.35 | 2 | 13.34 |
| Lay out branch takeoffs. Install and seal takeoffs with B collars on trunk. Install trunk to ceiling | 157 | 33.35 | 2 | 174.53 |
| Seal all joints of elbows | 12 | 33.35 | 1 | 6.67 |
| Seal trunk connections | 27 | 33.35 | 1 | 15.01 |
| Seal supply plenum, around screw connections, with mastic | 10 | 33.35 | 1 | 5.56 |
| Install boot for ceiling registers at first floor | 20 | 33.35 | 1 | 11.12 |
| Install and seal elbow to collar | 31 | 33.35 | 1 | 17.23 |
| Install flex duct | 72 | 33.35 | 1 | 40.02 |
| **TOTALS** | **529** | | | **398.53** |

[a] Labor rate based on skilled worker classification in the 2015 *RS Means Residential Cost Data* handbook and does not include overhead and profit

Because the traditional trunk-and-branch system ran perpendicular to the floor framing, a constructed ceiling chase was necessary to house and conceal the ducts (Figure 22 and Figure 23). The labor and materials for the chase were documented (Table 11 and Table 12) and need to be considered when comparing total costs of each system. Both the trunk-and-branch and 2.5-in. PnP system required the chase, whereas the smaller-diameter 2-in. PnP did not, which therefore demonstrates additional cost savings outside of the actual duct installation.


**Figure 22. Framed ceiling chase**

**Figure 23. Trunk duct in chase**

**Table 11. Ceiling Chase Materials Costs**

| Material | Quantity | Cost Per Unit ($) | Total Cost ($) |
|---|---|---|---|
| ½-in. sheetrock (4 x 8) | 3 | 9.34 | 28.02 |
| 2 x 4 x 10-ft studs | 9 | 4.17 | 37.53 |
| Drywall tape and mud | 36 ft | | 2.00 (est.) |
| **TOTAL** | | | **67.55** |

**Table 12. Ceiling Chase Construction Labor Cost**

| Description | Time (min) | Labor Rate $/h[a] | Crew Size | Assembly Labor Cost ($) |
|---|---|---|---|---|
| Install 16-in. rips of drywall to ceiling and wall | 43.00 | 33.35 | 2.00 | 47.80 |
| Tape and coat inside corner of bulkhead | 15.00 | 33.35 | 1.00 | 8.34 |
| Frame and install face and soffit of bulkhead | 121.00 | 33.35 | 2.00 | 134.51 |
| | | | **TOTAL** | **190.65** |

[a] Labor rate based on skilled worker classification in the 2015 *RS Means Residential Cost Data* handbook and does not include overhead and profit

## 3.3 Design Considerations for the PnP System

The PnP system uses a home-run distribution strategy wherein a plenum manifold is installed directly over the AHU supply opening (Figure 24). The manifold is outfitted with ports that the individual duct runs tap into. These runs are then installed to their final locations in the home. A distinct benefit of the PnP system is the ability of the smaller diameter ducts to be routed through standard 2 x 4 wall framing. This advantage allows for final register placement to be in high-sidewall locations in lieu of the floor registers; this is preferable from the standpoint of air mixing, and it provides more flexibility in furniture placement throughout the room.

For more detailed information on completing a PnP duct system design based on this methodology, see the Design Method Instruction Sheet in Appendix B.

**Figure 24. Plenum manifold with takeoffs**

## 3.4 Time and Motion Study of the 2.5-in. PnP System

A design was created for the pipe distribution based on the design methodology (Figure 25). The design called for eight runs from the AHU to the final outlet locations in the house. Use of the 2.5-in. PVC pipe limited the routing ability because of the size and rigidity of the material. This forced most the system to be installed in a bulkhead along the exterior wall of the building. This bulkhead was the same that was used for the trunk-and-branch study.

The PnP systems were installed by the same two tradespeople who performed the trunk-and-branch installation. A plenum manifold was fabricated prior to the system installation. The manifold box materials and fabrication labor are included in the costs for the prototype system, based on available retail costs and a standard labor rate of $33.35 person/h. The manifold box is envisioned to be a stand-alone, off-the-shelf product that would simply fit over the AHU and be ready to go. The installation began with the technician laying out the register outlet locations for the second floor. All runs for the second floor used a high-sidewall distribution strategy. Once the locations were established, a 3-in. hole saw was used to drill a hole through the subfloor and bottom plate of the wall to allow the vertical pipe to pass through and feed the sidewall register outlets. The high-sidewall register outlets were set in their final locations and fastened to the framing with a metal strap and screws. Mounting blocks with holes predrilled to fit the pipe were then fastened in the bulkhead area (Figure 26). These blocks aid in the pipe installation and hold the pipe in place permanently.

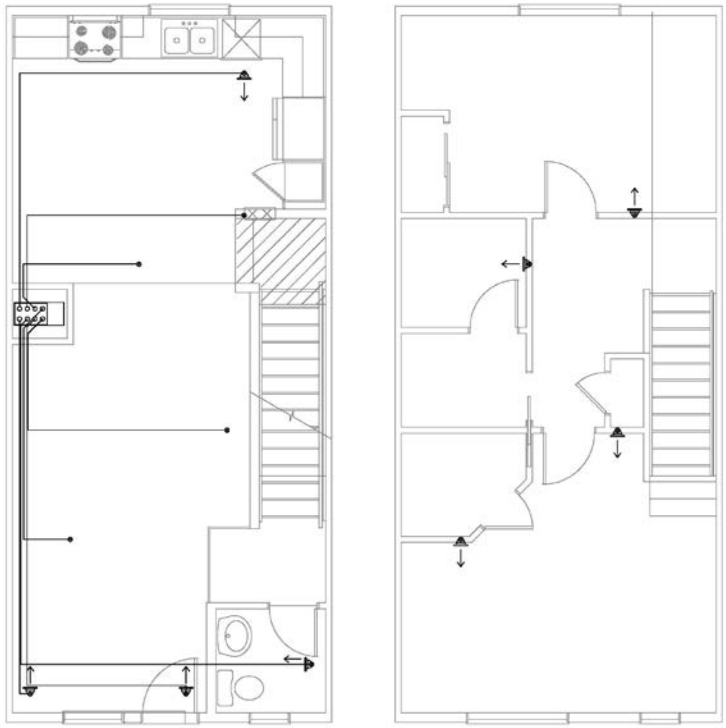

**Figure 25. Two-and-one-half-inch PnP system layout (not to scale)**

**Figure 26. Pipe support blocks**

The remaining pipe was then run from the AHU mechanical closet to the duct outlet locations. Following the installation of all runs, the final connections to the manifold ports were completed (Figure 27).

**Figure 27. Final connections at plenum manifold**

Table 13 and Table 14 show the material and labor costs of the 2.5-in. PnP system installation.

**Table 13. Two-and-One-Half-Inch PnP Materials Costs**

| Material | Quantity | Cost Per Unit ($) | Total Cost ($) |
|---|---|---|---|
| 2.5-in.–10-ft PVC Sch 40 pipe | 21 | 13.37 | 280.77 |
| 2 .5-in. PVC Sch 40 elbow 90° | 37 | 4.72 | 174.64 |
| 2.5-in. PVC Sch 40 elbow 45° | 6 | 4.73 | 28.38 |
| 2.5-in. PVC Sch 40 coupler | 14 | 2.15 | 30.1 |
| PVC cement | 1 | 5.88 | 5.88 |
| Wood support blocks | 4 | 2.37 | 9.48 |
| 8-port manifold | 1 | 89.69 | 89.69 |
| **Total** | | | **613.94** |

**Table 14. Two-and-One-Half-Inch PnP System Labor Cost**

| Description | Time/Person (min) | Labor Rate $/h[a] | Crew Size | Assembly Labor Cost ($) |
|---|---|---|---|---|
| Lay out and cut holes in second floor | 14 | 33.35 | 1 | 7.78 |
| Install second-floor outlets with metal support strips | 11 | 33.35 | 1 | 6.11 |
| Mount duct guide/duct supports | 10 | 33.35 | 1 | 5.56 |
| Install ducts on left side of closet | 44 | 33.35 | 2 | 48.91 |
| Install ducts on right side of closet | 27 | 33.35 | 2 | 30.02 |
| Connect ducts to plenum manifold in closet | 37 | 33.35 | 2 | 41.13 |
| **TOTALS** | **143** | | | **139.51** |

[a] Labor rate based on skilled worker classification in the 2015 *RS Means Residential Cost Data* handbook and does not include overhead and profit

## 3.5 Time and Motion Study of the 2-in. PnP System

The 2-in. PnP method followed a strategy that is similar to the 2.5-in. PnP system with each duct run being routed from the AHU to each outlet location; however, the routing throughout the house was different (Figure 28). A distinct advantage of using the smaller diameter, 2-in. piping was the ability to distribute the pipe both parallel and perpendicular to the open web floor framing. This flexibility allowed the system to be installed without any type of constructed bulkhead, which saves both time and money. The smaller diameter pipe does, however, require more runs to certain locations because of the reduced airflow through the pipe.

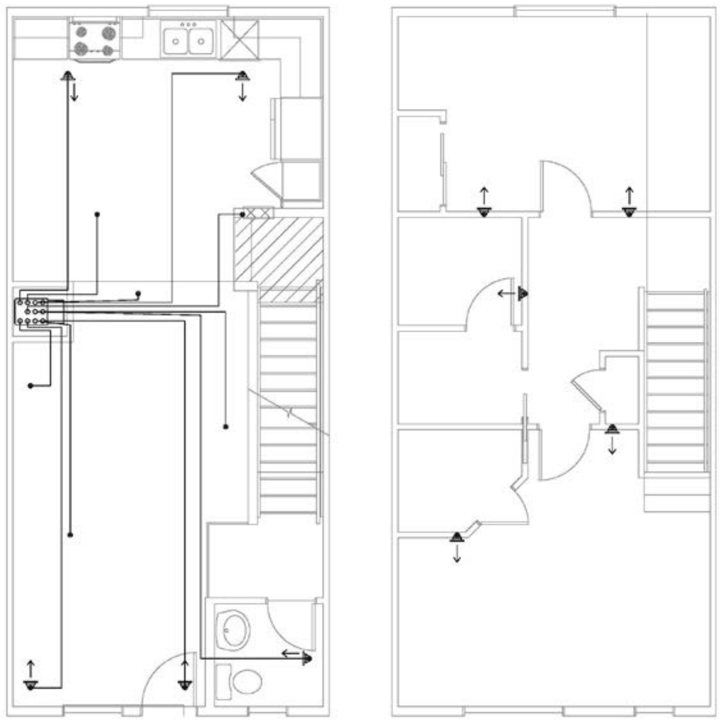

**Figure 28. Two-inch PnP system layout (not to scale)**

This system was installed in a fashion that is similar to that of the 2.5-in. system, with the final high sidewall outlets installed first and all of the subsequent piping routed back to the AHU closet (Figure 29).

**Figure 29. High-sidewall outlets**

A fabricated manifold guide that matched the top of the plenum manifold was installed directly to the ceiling above the AHU. This guide helps hold the pipe in place at the ceiling prior to making the final connections to the plenum (Figure 30.)

**Figure 30. Ceiling support guide**

The plenum manifold was then installed and sealed to the top of the AHU (Figure 31). The 2-in. PnP manifold required 11 ports to feed the system. It is understood that additional duct runs or a larger mechanical closet might be necessary to adequately serve larger or more complex homes. In these instances, the manifold port numbers might need to be adjusted along with the system design. Ideally, the manifold box will be equipped with pre-punched knockout holes to accommodate small field adjustments if necessary.

**Figure 31. Two-inch PnP manifold**

All the pipe connections between the ceiling guide and manifold were then installed (Figure 32).

**Figure 32. Final connections at the manifold**

The smaller diameter piping provided more flexibility when routing through the framing of the house, and it was easier to handle and install because of the flexibility and size of the material compared to the 2.5-in. PVC piping (Figure 33).

**Figure 33. Pipe distribution through floor**

Table 15 and Table 16 show the material and labor costs of installing the 2-in. PnP duct system.

**Table 15. Two-inch PnP Material Costs**

| Material | Quantity | Cost Per Unit ($) | Total Cost ($) |
|---|---|---|---|
| 2-in.–10 ft ABS PE pipe | 25 | 9.62 | 240.5 |
| 2-in. ABS elbow 90 | 50 | 1.52 | 76 |
| 2-in. ABS elbow 45 | 1 | 0.9 | 0.9 |
| 2-in. ABS coupler | 8 | 0.9 | 7.2 |
| "J" support hooks | 29 | 0.84 | 24.36 |
| Ceiling support panel | 1 | 8.94 | 8.94 |
| 11-port manifold | 1 | 82.37 | 82.37 |
| **TOTAL** | | | **440.27** |

**Table 16. PnP System Labor Cost**

| Description | Time/Person (min) | Labor Rate $/h[a] | Crew Size | Assembly Labor Cost ($) |
|---|---|---|---|---|
| Lay out and cut holes in second floor | 6 | 33.35 | 1 | 3.34 |
| Install second-floor outlets with metal support strips | 4 | 33.35 | 1 | 2.22 |
| Install ducts above closet to connect to plenum manifold | 21 | 33.35 | 2 | 23.35 |
| Install duct runouts on left side of closet | 70 | 33.35 | 2 | 77.82 |
| Install ducts on right side of closet | 42 | 33.35 | 2 | 46.69 |
| Cut ducts to desired lengths | 13 | 33.35 | 2 | 14.45 |
| Install unit and connect ducts to plenum manifold | 24 | 33.35 | 2 | 26.68 |
| **TOTAL** | | | | **194.55** |

[a] Labor rate based on skilled worker classification in the 2015 *RS Means Residential Cost Data* handbook and does not include overhead and profit

# 4 Performance Evaluation

A simulation exercise was developed to determine whether the proposed PnP system—which has benefits to costs, installation, and a simplified design methodology—could perform relatively similar or better than the trunk-and-branch systems that are widely used in homes nationally.

Overall, the results of the simulation effort suggest great potential for the PnP duct system. In most of the cases simulated, the PnP duct system performed as well as or better than the traditional trunk-and-branch system. Although the absolute performances against industry standards for temperature uniformity were poor in some cases, they were comparable to previously-studied homes with conventional duct systems. Differences in seasonal loads resulted in some zones being over- or under-conditioned.

Duct diameters for the trunk-and-branch system were sized per ACCA *Manual D*. The resultant branch duct sizes were between 3 in. and 6 in., which are less than those typically used in the industry. Small ducts also have a greater relative difference in size. The relative area increase between a 3-in.–4-in. duct is 78%, whereas the relative increase between a 6-in. and 7-in. duct is 36%. This highlights the need for duct manufactures to consider manufacturing smaller ducts and intermediate sizes for smaller ducts (e.g., 3.5 in. or 4.5 in.). Intermediate duct sizes would allow trunk-and-branch systems to have greater control over their natural balancing.

The simulations were also used to evaluate design methodologies that incremented the number of duct runs to each zone to account for variations in design loads. A total of four duct designs were simulated in three climate zones: equal flow to each outlet, length-based flow prediction, length- and fittings-based flow predictions, and with and without temperature loss compensation. Ultimately, the simulation results alone did not show a conclusive winner among the design candidates. The basic design approaches generally performed worse. The flow predicted with and without accounting for temperature loss typically resulted in marginally better comfort; however, insignificant performance differences were predicted by these two simulations. A strong conclusion of the simulation work is that differences in seasonal and peak loads are a greater driver in comfort than the selected design method. This disparity was most pronounced in climates with large differences between heating and cooling loads. A design method was selected for relative accuracy, simplicity, and reproducibility.

This project makes use of relatively new AFN components in EnergyPlus to simulate air distribution systems and interzonal mixing, and this report acts as a case study for using these components in a residential energy model. Descriptions are given about how each model feature was handled. Model results were compared to an instrumented test house, and there was generally good agreement. The team also made heavy use of scripting to automate the analysis. This enabled broader analysis and facilitated the re-creation of the full modeling process—from geometry through to plotting and data analysis—as the inputs were refined and debugged.

Simulation outputs for duct supply temperature and room air temperature were compared to measured values from the unoccupied lab house. The simulated supply air temperature of the majority of the ducts was within 2.0°F of the measured value. The room-to-room temperature difference for the model was compared to measured data, and it showed a root mean square error of 15%.

The team successfully implemented the AFN functions to compare the effects of variable duct system parameters and home interior configurations. Interior door state, system layout, duct U-value, duct leakage, and internal gains were examined individually to assess their individual effects on system balancing and temperature uniformity. Each parameter's significance was isolated and shown to have important influence on room-to-room temperature uniformity.

### 4.1 Modeling Methods

To test the ability of the PnP system and design methodology to provide comfort under a variety of climate zones, the team ran a set of detailed thermal simulations. These simulations allowed the team to directly compare several candidates for the design methodology and to compare the PnP system to a traditional trunk-and-branch duct system. Specifically, the focus of the modeling and analysis was to determine relative temperature uniformity among rooms and a central thermostat in a home. Renderings of the three-dimensional model and duct layout are shown in Figure 34.

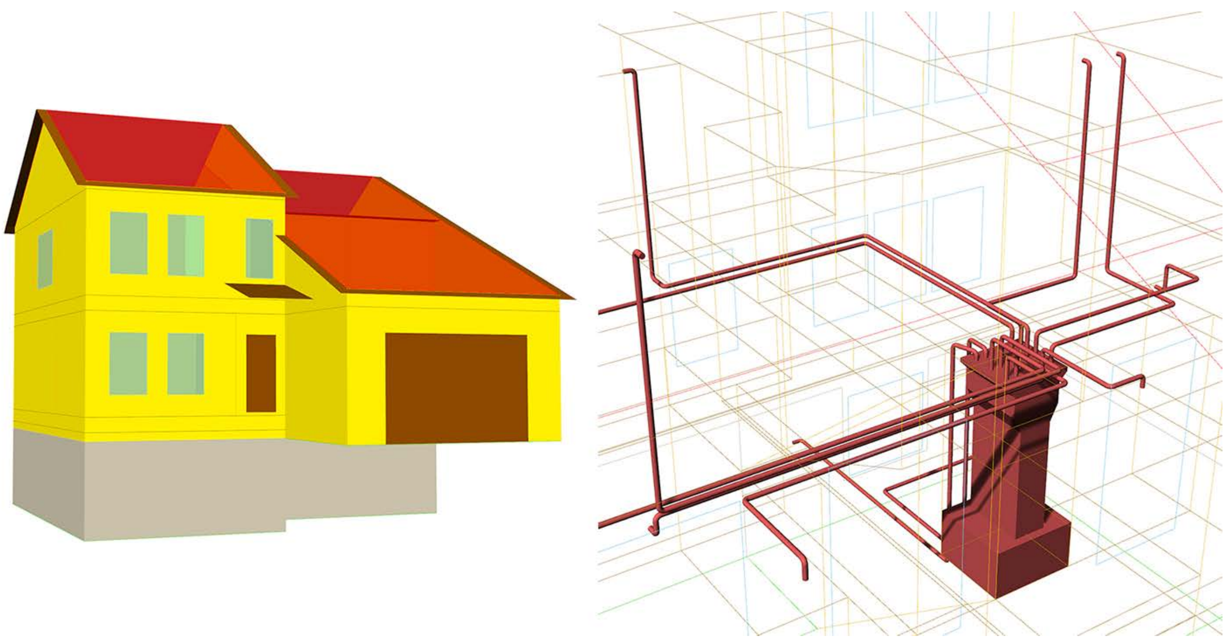

**Figure 34. Screenshots of three-dimensional model showing geometry and PnP system**

The three primary goals of the simulations were to:

- Predict individual room air temperatures
- Predict airflow distribution as it relates to the duct system
- Quantify air-mixing among zones.

This led the team choosing EnergyPlus (version 8.6) with AFN to achieve these target outcomes. Other software packages using the EnergyPlus engine were considered, including BEopt™ and

OpenStudio, but neither currently support AFN. Additionally, it was advantageous that the AFN could simulate the room-to-room air mixing and duct system in situ without supplemental external calculations.

The primary purpose of using energy simulations was to simulate the performance of the air distribution system, return-air mixing, and zone coupling to predict the air temperature in each zone of the house. It was desirable to allow the simulation to determine the air distribution balancing per duct system parameters and for the interior conditions that would affect temperature uniformity, such as whether interior doors were open or closed.

Additionally, the team required that the models be generated such that a wide array of parameters could be easily manipulated. The focus of the study was to compare duct system configurations among differing interior conditions, enclosures levels, operating assumptions, etc.

A 2-week-run period was chosen, one week for each of the summer and winter months. The team considered running an entire annual simulation; however, the run time would have been prohibitive for the number of simulations. Running one 2-week period took 4–12 min of simulation time. One reason for the difference in run time appeared to be the amount of time the air handling system was operating per model. When the AFN was calculating the entire distribution system, it slowed down the simulation rate. Table 17 summarizes the overall simulation parameters.

**Table 17. Simulation Parameters**

| | |
|---|---|
| **Time step** | 1 min |
| **EnergyPlus version** | 8.6 |
| **Heat balance algorithm** | Conduction transfer function |
| **System control** | Energy management system thermostat simulation |
| **Air temperature capacitance multiplier** | 8 |
| **AFN control** | Multizone with distribution |
| **Summer run period** | July 15–31 |
| **Winter run period** | Jan. 15–31 |

The house geometry chosen for the simulation was based on the Pittsburgh unoccupied lab house. This geometry was chosen because it would allow for the comparison to measured data, thus ensuring accurate models. In addition, IBACOS possesses extensive knowledge of the house's performance based on past research projects conducted there; and it offers a wide variety of load conditions, with some zones having significant southern or western glazing relative to floor area.

The basis of comparison among simulations was room-to-room temperature uniformity. According to ACCA *Manual RS* (Rutkowski 1997), a well-performing space-conditioning system should keep each zone within 4°F of each other zone during heating operation and within 6°F during cooling operation. This metric provides a minimum comfort requirement for the residential setting. ACCA *Manual RS* also specifies that each zone should be within 2°F of the thermostat during the winter and within 3°F of the thermostat during the summer. This metric can be more difficult to achieve if the zone location of the thermostat is one of the warmer or cooler zones in the house. As shown in the following results, using this metric would have resulted in more frequent periods when the uniformity within the home deviated from ACCA guidance; however, the relative system-to-system performance remains similar, and this is the primary consideration of this project. Also, thermostat location was not considered as an independent variable and was held to one location for all models, which would have made evaluating room-to-thermostat deviation more appropriate.

Humidity levels were not considered in this analysis because of the complexity and potential for error in simulating exact humidity levels. Including humidity levels might have clouded the analysis, which sought to evaluate the differences in air delivery systems.

The following sections describe in detail how each component of the model was created. For more detail regarding the setup and configuration of the AFN in EnergyPlus, see Appendix A: Airflow Network Setup Lessons Learned.

### 4.1.1 Geometry

The geometry consists of multiple components, including both thermal zones, surfaces, and fenestrations. AFN objects associated with the surfaces were matched when necessary, such as for doors, large openings, and horizontal openings. Spaces directly conditioned are indicated as well as locations and types of openings between spaces. Thermal zoning follows interior partition lines, with interstitial spaces such as floor cavities and attics also included. Note that horizontal openings were used to connect floors. Interior doors were modeled using simple openings, with the crack factor parameter used to account for opening and closing. Figure 35 diagrams the zoning and surface types of the model.

The level of geometry detail has not been studied regarding its uncertainty contribution to the results of the simulations. It might have been possible to simulate rooms connected with large openings with single thermal zones and seen similar results because the measured data indicated that certain rooms nearly track each other in terms of temperature; however, comparisons to measured data suggest that the simulations accurately represent the mixing through such large openings, and simulation run time was not a factor.

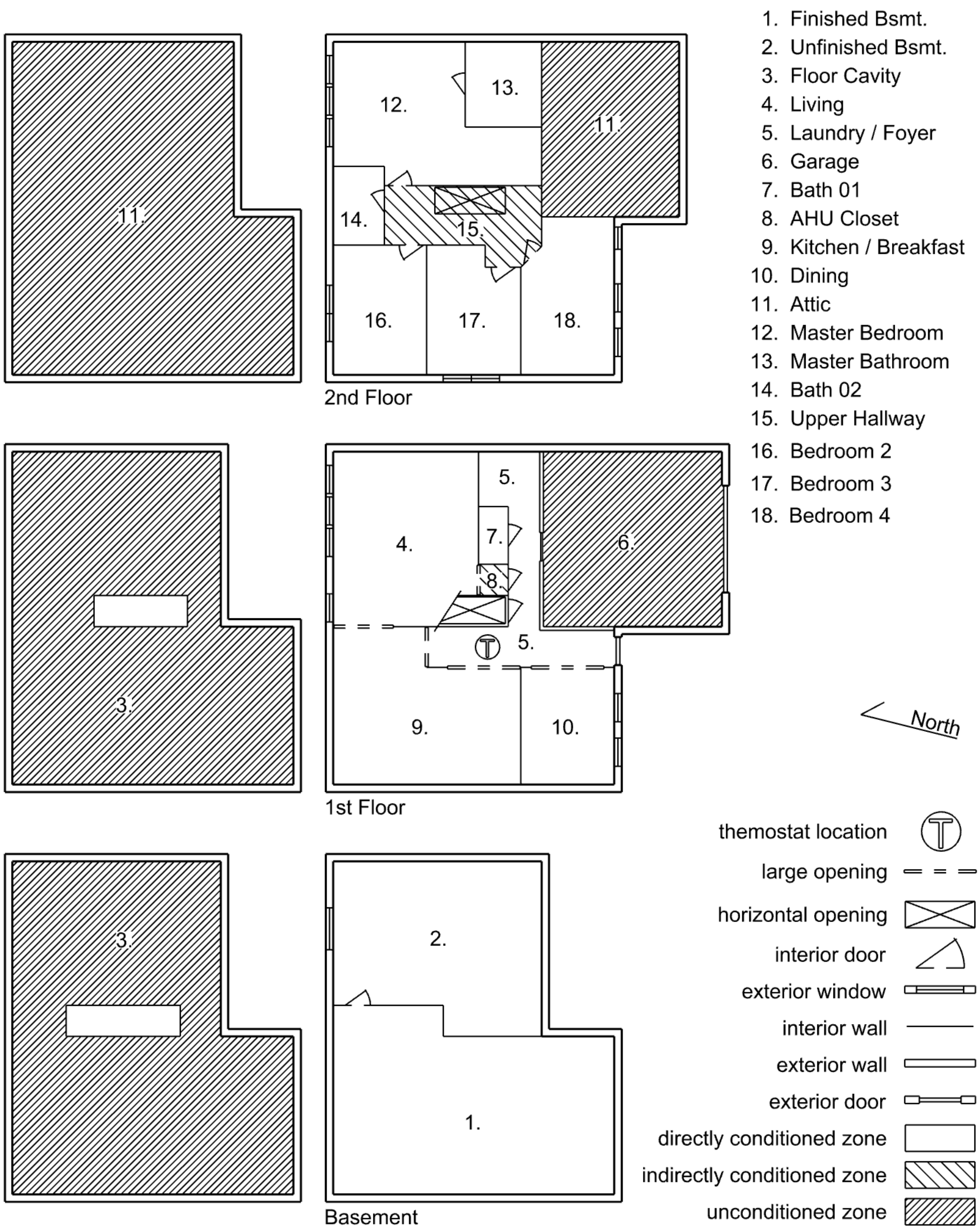


**Figure 35. Model zoning diagram**

### 4.1.2 Air Distribution and Mixing

The air delivery system was modeled using AFN distribution components. The duct runouts were modeled as duct segments that were linked together. The ducts were modeled as three-dimensional lines in Rhinoceros, and a script was written to split them into duct segments so that their heat loss and/or leakage could be associated with the appropriate zone. At each vertex along the lines, a fitting loss coefficient was added to the duct segment. A script compiled the split curve parameters—length, zone, number of fittings, location, terminal zone—which was used to create the appropriate EnergyPlus input objects.

*Air Distribution Layout*

Two types of distribution systems were modeled: (1) A traditional trunk-and-branch-style system with flex duct runouts from a central sheet metal trunk and (2) the PnP duct system. Material properties were varied per the duct system as were the layout configurations. The baseline traditional system was chosen because of its prevalence in production-built homes. The climate zones for the study had effects on the distribution systems in different ways. The trunk-and-branch system varied the diameters of the runout ducts per the loads calculated by *Manual J*; and for the PnP system, the number of ducts varied with respect to the load. Two template files were created to accommodate the two distribution configurations and designs for each of the three climate zones. The AHU for both systems was located on the first floor, with the ductwork for the PnP system primarily located in the cavity between the first and second floors and the ductwork for the trunk-and-branch system primarily located in the cavity between the first floor and the basement. Figure 36 shows a diagram of each distribution system.

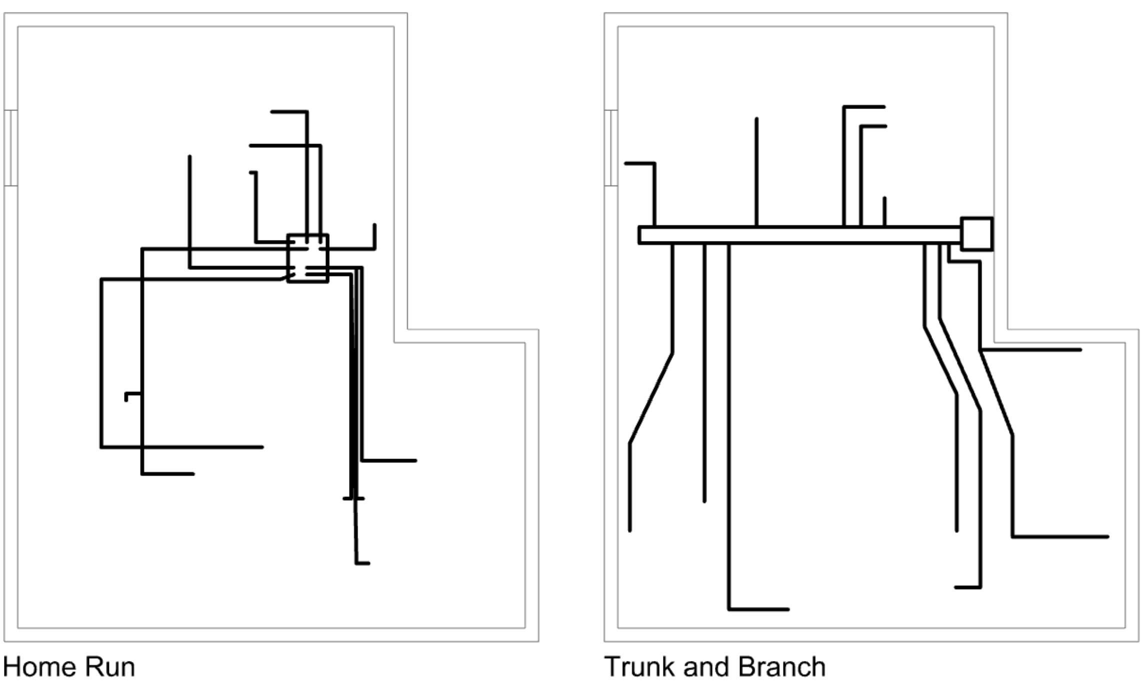


**Figure 36. Duct layouts: PnP (left) and trunk-and-branch (right)**

The static pressure in the main plenum, or main splitter box, was considered. Figure 37 and Figure 38 show the static pressure in the plenum during system operation (both at 600 CFM). The static pressure for the PnP system approaches 0.5 in. of water, whereas the trunk-and-branch system had a static pressure closer to 0.1 in. of water.

The low static pressure in the trunk-and-branch system is caused by the low airflow. Typical diameters of duct runouts range from 6–12 in., but these are not appropriate for achieving adequate air velocities in low-load homes. The ducts for the trunk-and-branch system were sized per *Manual D*, with a minimum diameter of 3 in. Duct diameters ranged from 3–6 in., which are very small compared to those used by a typical builder. This illustrates the fact that builders and duct manufacturers must adapt or think of new distribution methods to be able to maintain comfort as airflows decrease.

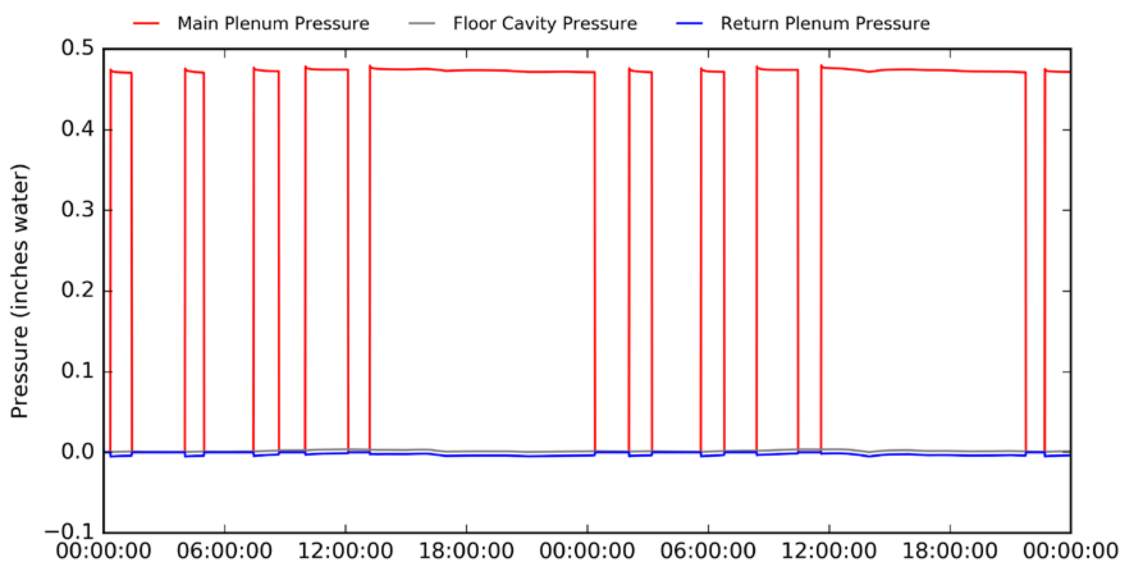


**Figure 37. Static pressure in the PnP system**

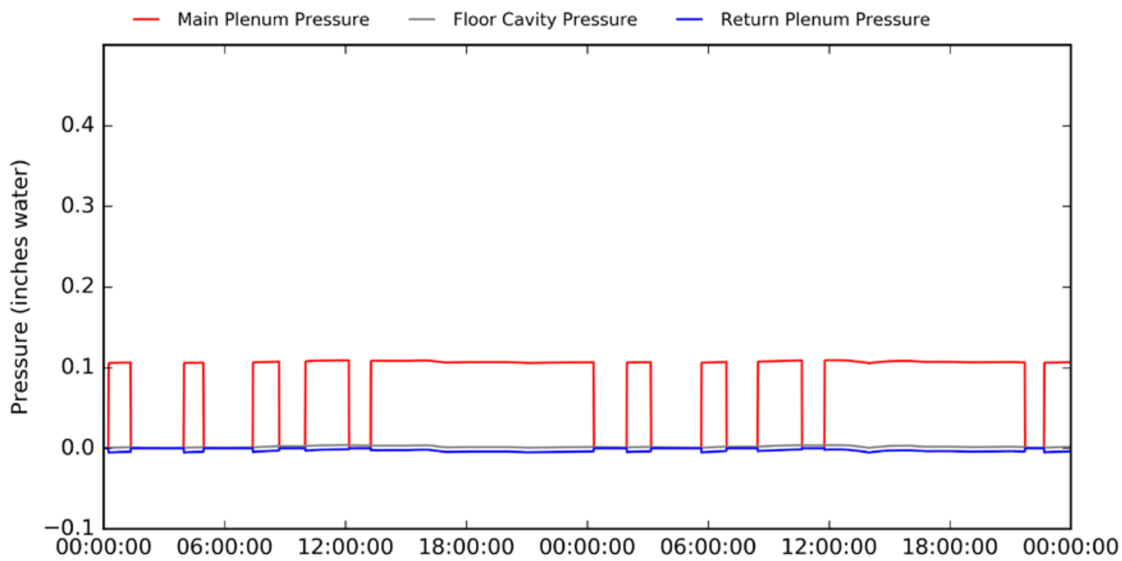


**Figure 38. Static pressure in the trunk-and-branch system**

### *HVAC System Capacity and Airflow*

For the simulation runs, the heating and cooling capacity was specified based on *Manual J* load sizes. Exact loads were rounded to the nearest ½ t. The fan airflow was then calculated by assuming 400 CFM/t of cooling. Because of limitations in the AFN, a single-fan airflow rate had to be used for both heating and cooling. Because the cooling number is more sensitive, and because EnergyPlus places requirements on the CFM/t to not have unrealistic operation, the cooling airflow was used for both modes. Table 18 shows a summary of each load, capacity, and airflow.

**Table 18. Design Load, System Capacity, and Airflow for Each House Type**

| | Climate Zone 2 | Climate Zone 3 | Climate Zone 5 |
|---|---|---|---|
| **Code** | 2012 | 2012 | 2012 |
| **Heating load (Btu/h)** | 17,010 | 16,996 | 28,250 |
| **Cooling load** | 13,359 | 14,804 | 10,533 |
| **Heating capacity** | 18,000 | 18,000 | 30,000 |
| **Cooling capacity** | 18,000 | 18,000 | 18,000 |
| **Airflow (CFM)** | 600 | 600 | 675 |

One city was chosen to represent each of the climate zones: Orlando, Florida (Climate Zone 2); Fresno, California (Climate Zone 3); and Denver, Colorado (Climate Zone 5). These cities were chosen because of their differences in climates and because they are areas with significant new construction. Note that Climate Zone 3 has a higher cooling load relative to Climate Zone 2 because of a higher design temperature.

### *Duct Leakage*

Leakage can have a significant impact on the amount of energy delivered to a space. A benefit of the PnP system is the lack of any significant leakage because of the connection mechanism; it is a product solution to duct leakage. Trunk-and-branch duct systems are knowingly fraught with leakage, and this is particularly a problem when the leakage makes its way to the outside. Although all the duct systems simulated as part of this research are in conditioned spaces, the loss of airflow because of leakage affects the delivered energy balance and thus is important when considering temperature uniformity. An AFN:distribution:leak component was added at each takeoff from the main trunk for each duct in the floor cavity between the basement and first floors where the main trunk is located. Figure 39 illustrates how this is set up for one takeoff in a model.

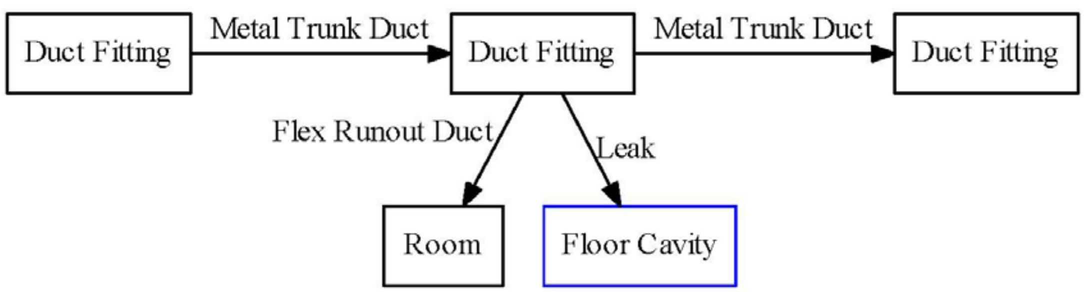


**Figure 39. Diagram of leak configuration in AFN model**

### *Infiltration*

Air infiltration was modeled using AFN. A whole-house Effective leakage area (ELA) value was derived from ACH50 leakage limits set by the 2012 IECC. Equation (7), taken from Sherman and Grimsrud (1980) describes the conversion from ACH50 to ELA in square meters. ELA AFN components were associated with each exterior wall—the surfaces with an outside boundary condition—wherein the estimated total equivalent ELA was proportioned to each surface by its area relative to the total exterior surface area.

$$ELA = \frac{Q_r}{\sqrt{2 * \Delta P_{ref}/\rho}} = \frac{Q_r}{\sqrt{100/1.225}} = Q_r * \sqrt{0.01225} \tag{7}$$

where:

$Q_r$ = airflow rate at reference pressure, $m^3/s$

$ELA$ = effective leakage area, $cm^2$

$\rho$ = air density, kg/m$^3$

$\Delta P_{ref}$ = reference pressure difference, Pa.

Table 19 lists the leakage limits by climate zone taken from Table R402.4.1.1 of the IECC 2012, the associated airflow rate at the reference pressure (50 Pa), and the calculated ELA in square meters input to the simulations for their respective climate zones.

**Table 19. Climate Zone, IECC 2012 Air Leakages, and ELA Model Inputs**

| Climate Zone | ACH50 | Q (m$^3$/s) | ELA (m$^2$) |
|---|---|---|---|
| 1–2 | 5 | 1.06 | 0.117 |
| 3–8 | 3 | 0.63 | 0.070 |

To confirm that the simulated infiltration was within a reasonable range, the simulation output was compared to estimates using Equation (8), based on Sherman and Grimsrud (1980), the basic infiltration model, to estimate the airflow rate due to infiltration:

$$Q = \frac{ELA}{1000}\sqrt{C_s \Delta t + C_w U^2} \tag{8}$$

where:

$Q$ = airflow rate, m$^3$/s

$ELA$ = effective leakage area, cm$^2$

$C_s$ = stack coefficient (L/s)$^2$/(cm$^4$.K)

$\Delta T$ = average indoor-outdoor temperature difference for time interval of calculation, K

$C_w$ = wind coefficient, (L/s)$^2$/[cm$^4$.(m/s)$^2$]

$U$ = average wind speed measured at local weather station for time interval of calculation, m/s.

Using a wind coefficient for shelter class 4 and stack coefficient for a two-story building, the equation solves to leakage flow rates summarized in Table 20 for each season.

**Table 20. Infiltration Estimates for Average Conditions Using Basic Infiltration Model**

| Season | ELA (cm$^2$) | T-In (C) | T-Out (C) | Wind (U m/s) | Cs | Cw | Q (m$^3$/s) | CFM |
|---|---|---|---|---|---|---|---|---|
| Winter | 0.70 | 21.66 | 0 | 3.50 | 0.000290 | 0.000137 | 0.063 | 133.08 |
| Summer | 0.70 | 24 | 27 | 3.50 | 0.000290 | 0.000137 | 0.036 | 75.30 |

Figure 40 shows the simulations in-, out- and net infiltration airflow for comparison during a 12-h period. The system is continuously cycling for the time periods represented in the plot, and subtle shifting of the leakage rate can be observed—decreasing when the system is on. The modeled air leakage never quite hits the 133-CFM predicted by the basic infiltration model in the winter, maxing out at 120 CFM. The same applies to the cooling leakage, which peaked at slightly less than 60 CFM; whereas the simple model predicted 75 CFM.

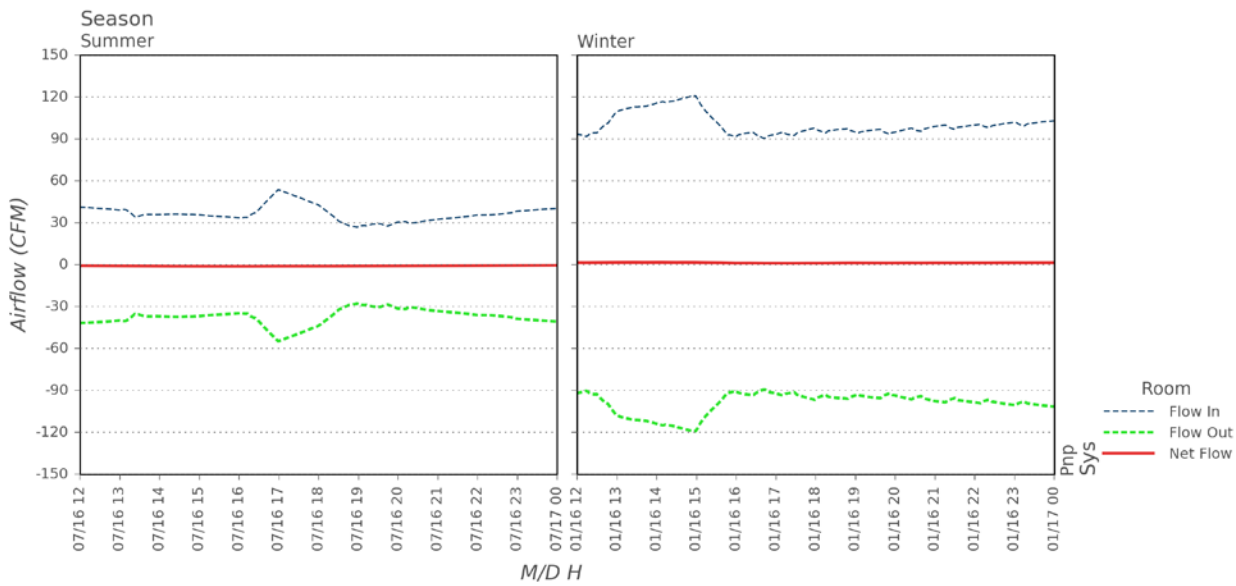


**Figure 40. Simulated infiltration totals for Climate Zone 5**

No additional mechanical ventilation was simulated as part of this exercise. The reason for this was to remove any potential factors that would have complicated the AFN and distribution system. Additionally, it is expected that the net effect of exhaust-only, or supply-only ventilation at the return, would be to slightly increase the overall house load without significantly affecting room-to-room temperature uniformity.

### *Zone Coupling Airflow*

Mixing among zones has a significant effect on the temperature uniformity of the home. Whether the doors are open or closed, for example, will impact the ability of a hot room to lose its heat to adjacent spaces. EnergyPlus traditionally has relied on zone-mixing objects that require simple assumptions about how much air mixing occurs among adjacent zones, and it does not easily adapt to dynamic thermal conditions. The AFN objects allow for openings to be specified that calculate the mixing according to pressure-balancing equations.

Three types of AFN components were used to model the transfer of air among spaces: simple openings, cracks, and horizontal openings. For interior doors, simple openings were applied to fenestration objects, and they modeled with both open and closed configurations as specified by the crack factor. A crack factor of 0.1 was suitable for simulating a closed door with undercut as was the case in the monitored home.

Figure 41 shows the airflows in and out of interior doors. The plot labels indicate the connected zones, with negative flow from the left zone to the right as labeled, and visa-versa for positive flows. For example, the “Foyer -> Bsmt Finished” during the summer period indicates flow into the basement when the system is off and from the basement into the foyer—which is the return zone—when the system is on. When the distribution system is off, a small amount of mixing occurs between zones through the doors. When the system turns on, the return airflows are visible—for example, the air returning from the unfinished basement is approximately 80 CFM.

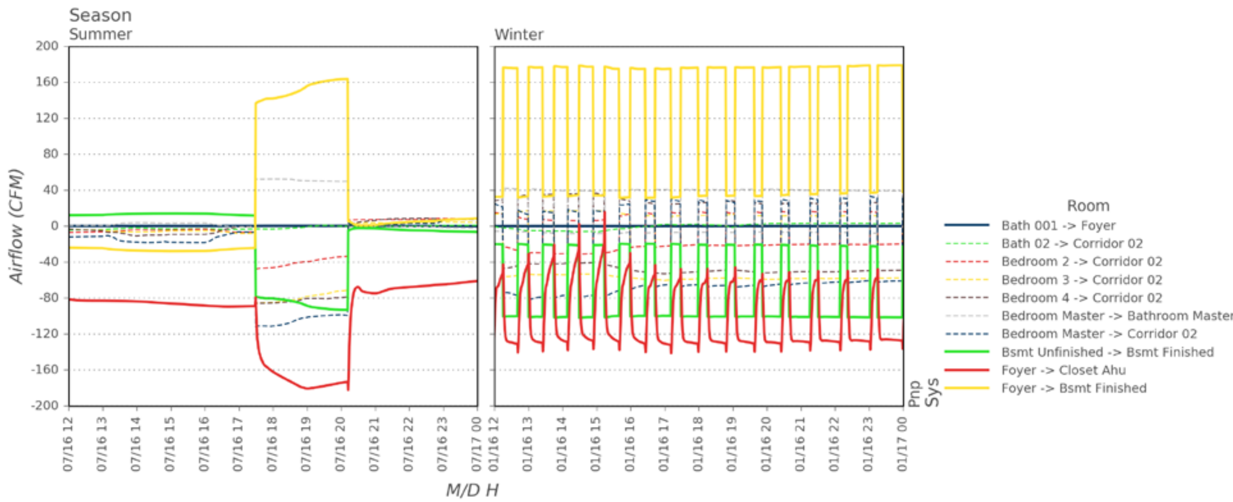


**Figure 41. Airflow through interior doors**

Figure 42 shows airflows through large openings. Note that the airflow from the living room into the kitchen is very large because all the air supplied to the second floor follows the path: living > kitchen > foyer.

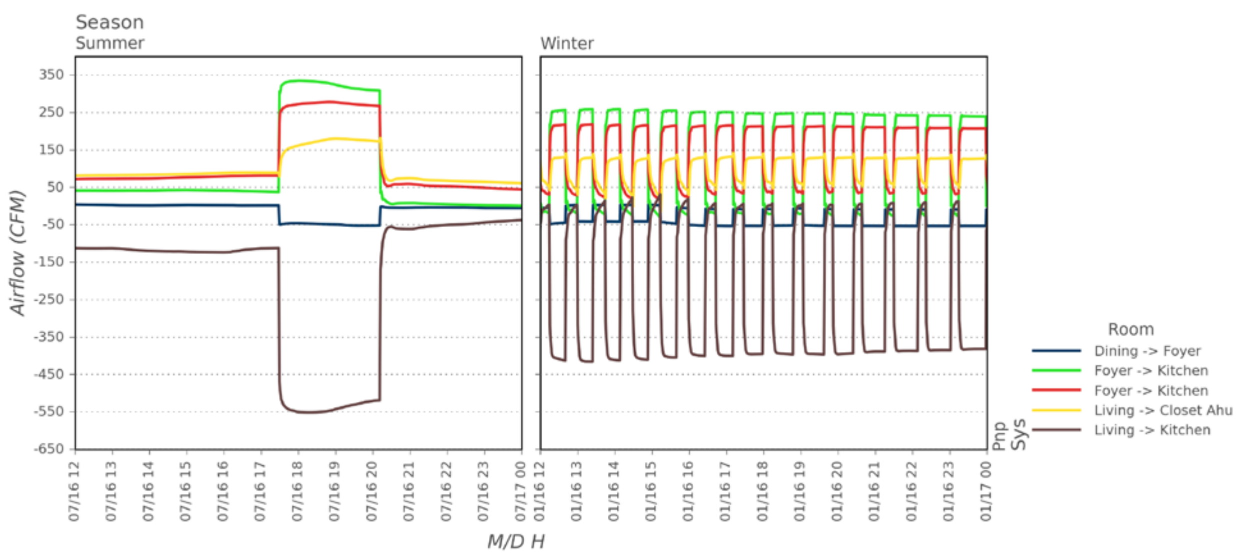


**Figure 42. Airflow through large openings**

Figure 43 shows the airflow through the horizontal opening between the first and second floor. During system run time, the airflow into the living zone is very close to the airflow into the second-floor zones, and any difference is caused by a combination of air making its way through leaks between the floor cavity and adjacent zones and leakage to the outside. When the system is off, marked by negative airflow, the air is flowing up to the second floor because of buoyancy. Note that during the winter period the airflow up to the second floor is significantly higher because the indoor-to-outdoor temperature difference is much larger.

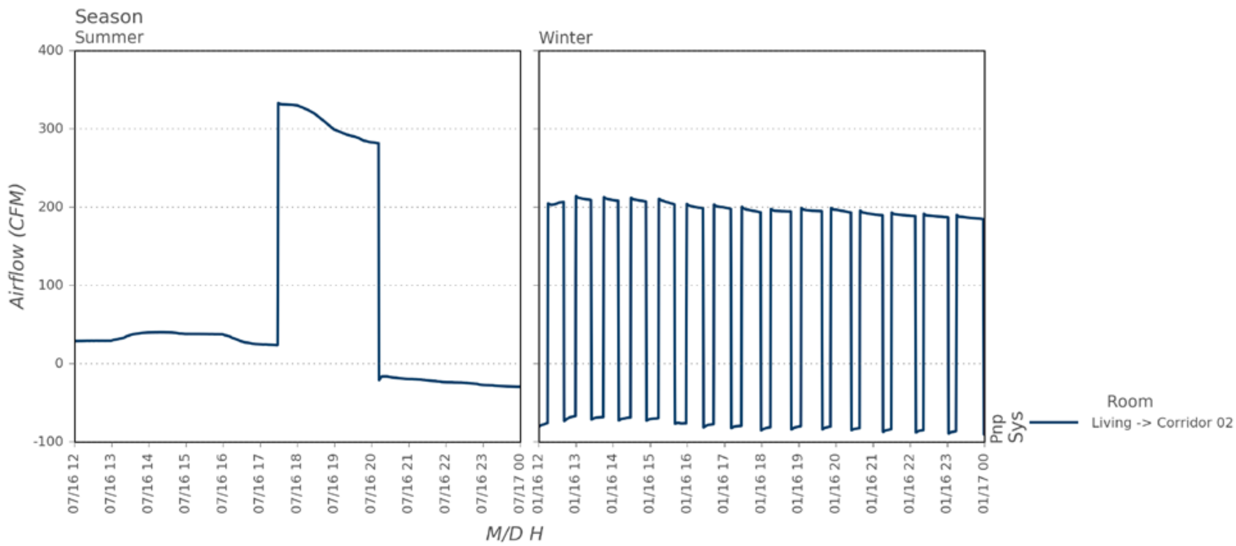


**Figure 43. Airflow through horizontal opening**

*Return Air Strategy*

The models were set up so that the air delivered was returned through adjacent rooms and hallways to a single return plenum connecting the foyer and AHU closet. The AFN model requires that each zone has a dedicated return duct connecting the conditioned zone to the return air mixer (main return plenum). To work around this, the model was set up so that the return ducts for all but the foyer zone were given 100-m ducts with very small diameters so that the air would return to the foyer zone by way of the AFN openings. The extraordinary length of the duct was chosen to ensure that no air returned through these pathways; rather, all the air would return through door undercuts and through hallways to the main return grille.

### *4.1.3 HVAC Equipment*

Simulating whole-house energy use was not a primary purpose of the thermal simulations. As such, basic heating and cooling objects were used. Heating was accomplished using an electric resistive-type coil in EnergyPlus, and cooling was accomplished using a basic direct expansion-type coil. Performance curves for the cooling coil were taken from BEopt. Operation of the heating and cooling equipment was accomplished by using an energy management system subroutine. Typically, EnergyPlus does not simulate the on/off cycling of conditioning equipment but rather relies on part-load conditions to simulate energy use. This assumption simplifies calculations for energy use prediction, but it is not suitable for understanding the impact of an air delivery system on comfort. To achieve real-world thermostat behavior, the energy management system program cycled the fan on and off according to a thermostat set point and deadband. The thermostat was located in the foyer zone for all models.

### 4.1.4 Internal Gains

Models were run with and without internal thermal gains to provide a realistic interior environment. The Building America simulation protocol was used by way of BEopt to distribute gains throughout the model zones. A BEopt model was created with the same specifications of the model, and each schedule and equipment set was extracted and adapted to the multizone simulation. A script was used to parse the values and distribute them according to space function and floor area. Table 21 describes the internal gains' design levels for each category. The miscellaneous electric loads, lights, domestic hot water distribution, and people were evenly distributed throughout the home, based on floor area. The domestic hot water was also included in the floor cavities. The dryer and washer were placed in the foyer zone. The refrigerator and range loads were in the kitchen, and the remaining water loads—sinks and showers—were distributed among the bathrooms.

**Table 21. Internal Gain Levels**

| Category | Total |
|---|---|
| Miscellaneous electric load | 673.95 W |
| Bathrooms | 7,944.58 W |
| Domestic hot water distribution | 116.17 W |
| Dishwasher | 10,589.51 W |
| Refrigerator | 65.09 W |
| Range | 262.46 W |
| Lights | 831.63 W |
| People | 3.23 People |
| Showers | 8,987.49 W |
| Sinks | 2,203.67 W |
| Dryer | 318.13 W |
| Washer | 8,027.91 W |

## 4.2 Validation

Data were collected from an unoccupied test house primarily to provide a real-world comparison for the simulations. The lab house also acted as a space to test installation methods and difficulty and to identify any unforeseen issues with an installed system. The data collection period was January–April 2016.

### 4.2.1 Unoccupied Test House Description

The unoccupied test house is located in Pittsburgh, Pennsylvania. This house, with front elevation shown in Figure 44, has been used for previous Building America research, and its performance characteristics are well understood. Table 22 shows the specifications for the unoccupied test house.

**Table 22. Unoccupied Test House Specifications**

| Assembly | Specifications |
|---|---|
| Concrete slab | R-10 continuous below slab |
| Basement/crawlspace walls | R-25 finished portion of basement, R-19.5 unfinished portion of basement |
| Above-grade exterior walls | 2 × 4 studs staggered in a 2 × 8 wall thickness, R-30 cavity insulation, R-10 continuous exterior sheathing with recessed furring strips, 5/8-in. drywall, framing fraction of 15%, whole-wall U-value = 0.024 Btu/h.ft$^2$ |
| Overhanging floors | N/A |
| Roof (location of insulation) | R-60 blown insulation in the floor of the vented attic |
| Exterior doors | R-5 |
| Windows | 306 ft$^2$, U-value = 0.24, solar heat gain coefficient = 0.22 |
| Building airtightness | 0.96 ACH50 |
| Mechanical ventilation | No mechanical ventilation was operated |
| Heating | Modulating 15,000–6,000 Btu/h gas furnace |
| Ductwork | Insulated 2-in.-diameter PVC duct |
| Appliances | ENERGY STAR®-rated refrigerator. No other appliances were operated during test period. |
| Lighting | Energy-efficient compact fluorescent lamp and light-emitting diode lighting |
| Photovoltaic system | 3.8-kW solar photovoltaic array with microinverters |


**Figure 44. Unoccupied lab house, located near Pittsburgh, Pennsylvania**

An existing AHU and a modulating gas furnace were used in the test configuration. The equipment can continuously vary the airflow rate and furnace capacity. This kind of equipment is ideal for the small-diameter PnP duct system. Most of the time, the system can operate at lower airflow rates, reducing static pressure and fan energy. The AHU was in an interior closet, central in the floor plan of the house.

### *4.2.2 Unoccupied Test House Measurement Methods*

Single-point testing and continuous monitoring were conducted in the unoccupied test house.

Single-point testing was conducted to measure the airflow at each duct and to identify any flow restrictions caused by opening and closing doors. Airflow was measured using a Davis Instruments Turbo Meter, which has a 2-in.-diameter turbine. The turbine was placed directly over the duct outlet to capture the entirety of the duct's flow.

Whole-house air leakage was measured using a Minneapolis Blower Door and Tectite 4.0 software. The whole-house air leakage value was converted to an ELA and used in the modeling effort. A test in 2011, at the completion of the home's construction, showed the whole-house air leakage to be 0.54 ACH50. The new measurement, taken in the summer of 2016, was 0.96 ACH50. The increase in air leakage might be caused by the house's age and the use of the house for conducting research, resulting in additional penetrations in the enclosure.

An Alnor LoFlo Balometer was used to measure the total system airflow. Total system airflow values were less than what could be measured by a typical AHU flow plate device (i.e., <400 CFM). Table 23 shows measurements and test equipment.

**Table 23. Measurements for Single-Point Tests**

| Measurement | Equipment Used |
|---|---|
| Forced airflow rate | TEC powered flow hood |
| Forced airflow velocity | Hot-wire anemometer, Davis Instruments Turbo Meter |
| Static pressure transducer | DG-700 |
| Whole-house air leakage | Minneapolis Blower Door, Tectite 4.0 |
| System airflow | Alnor LoFlo Balometer 6200D |

A data acquisition system was installed in the unoccupied test house to measure various aspects of the HVAC system operation, and comfort in the home. The data acquisition system consisted of a Campbell Scientific CR1000 data logger, AM16/32 multi-plexers, and IP communications hardware. In addition, several different sensors were installed. The specifics of the monitoring system are show in Table 24.

**Table 24. Measurement Types during Data-Collection Period**

| Measurement | Equipment Used | Measurement Uncertainty of Equipment[a] |
|---|---|---|
| Air temperature at 43 in. from the floor in each room | Type-T thermocouples (sensors housed in double wall measurement shield) | ±0.9°F |
| Temperature at each supply air terminal | Unshielded Type-T thermocouples located in center of airstream | ±0.9°F |
| Temperature at central return | Unshielded Type-T thermocouples | ±0.9°F |
| Run time of HVAC system: AHU and heat pump outdoor unit | Continental Control System WattNode | 0.5% |
| Global incident solar radiation on-site | LI-COR 200 silicon pyranometer | 5.0% |
| Outdoor temperature and relative humidity | Vaisala HMP60 in shielded enclosure | ±0.6°F, ±3.0% relative humidity |
| Static pressure at AHU supply and return | Pace Scientific P300 (±2-in. water column) | 2.0% |

[a] The measurement uncertainty listed in this table is the manufacturer's uncertainty.

### 4.2.3 Unoccupied Test House Airflows

Table 25 shows the terminal airflow measured in each room through the 2-in. ducts. These measurements were taken while the AHU was forced to operate at 40% and 100% of its maximum airflow using a debug mode in the thermostat. The relative airflow through each terminal remained stable at each airflow setting—i.e., increasing the airflow did not affect the percentage of total airflow going through each duct. For comparison of the modeled to measured data, the airflow at 165 total system flow needed to be determined. Because the AHU could not be set to this flow rate manually, the flow was instead calculated by multiplying the total airflow (165) by the fraction of the total determined by the 40% and 100% readings. The individual room airflow was calculated at 165 CFM by multiplying the fraction to each room by the total airflow. These values were then used for comparison to the AFN model.

**Table 25. Room Airflow Measurements**

| | Flow | | Fraction of Total | | At Test Value |
|---|---|---|---|---|---|
| | CFM | | | | CFM |
| Terminal | 40% | 100% | 40% | 100% | 165 |
| Living | 15 | 26 | 10% | 10% | 16 |
| Kitchen | 12 | 21 | 8% | 8% | 13 |
| Dining | 12 | 21 | 8% | 8% | 13 |
| Hall | 16 | 29 | 11% | 11% | 18 |
| Bedroom 4 R | 11 | 22 | 7% | 8% | 13 |
| Bedroom 4 L | 11 | 22 | 8% | 8% | 13 |
| Bedroom 3 | 11 | 19 | 7% | 7% | 12 |
| Bedroom 2 | 12 | 22 | 8% | 8% | 13 |
| Master Bed. R | 14 | 26 | 9% | 10% | 16 |
| Master Bed. L | 14 | 26 | 9% | 10% | 16 |
| Fin. Basement | 9 | 18 | 6% | 7% | 10 |
| Unfin. Basement | 11 | 22 | 7% | 8% | 13 |

The return strategy for the PnP system installed in the unoccupied lab house was to use the ½-in. door undercuts. To identify if there is any impact on system balancing or total airflow, the team conducted the following tests while the central blower was operational at 100% capacity (259 CFM):

- Measure the terminal CFM with doors open and doors closed for a bedroom with two duct runs.
- Measure the static pressure differential between the zone and hallway with the door closed for a bedroom with two duct runs.

These tests did not show any measurable difference in terminal CFM with doors open or closed. Additionally, any pressure differential between the zone and hallway was not measurable with the 0.1-Pa resolution of the DG-700 manometer. These results suggest that a ½-in. door undercut is an acceptable return strategy for most rooms in low-load homes with up to two ducts. For homes with more typical (higher) airflows, undercuts might not be sufficient. Because the AHU should be located centrally in the house, the return plenum should also be kept as small as possible.

The total system airflow was measured by using both the balometer and by summing the register measurements. Register measurements were made using the Davis Instruments TurboMeter. Results of these measurements are presented in Table 26. Also shown is the supply plenum pressure relative to ambient at each flow rate. The relatively low static pressure in the plenum box despite 2-in. ducts is a result of the smooth duct material and compact duct layout.

**Table 26. Total System Airflow**

| | Operation | |
|---|---|---|
| | 40% | 100% |
| Plenum Pressure (Pa) [in-H2O] | 26 [0.10] | 80 [0.32] |
| Total airflow (balometer) | 139 ± 4.2 | 259 ± 7.8 |
| Total airflow (sum of registers) | 148 | 274 |

### *4.2.4 Unoccupied Test House Stratification*

In addition to the sensors placed 43 in. above the floor height, two zones had sensors placed at 4 in. and 95 in. The purpose of these sensors was to measure any in-room stratification that might be occurring due to the high-sidewall outlets. Figure 45 shows the measured stratification compared to the outdoor temperature during the period from Feb. 1–20, 2016. A strong correlation is observed between outdoor temperature and the in-room stratification. Note that ASHRAE Standard 55 specifies the limit on ankle-to-head stratification to be 5.4°F. Most data fall below this limit despite the upper measurement being taken near 8 ft. The PnP duct system shows acceptable in-room stratification performance.

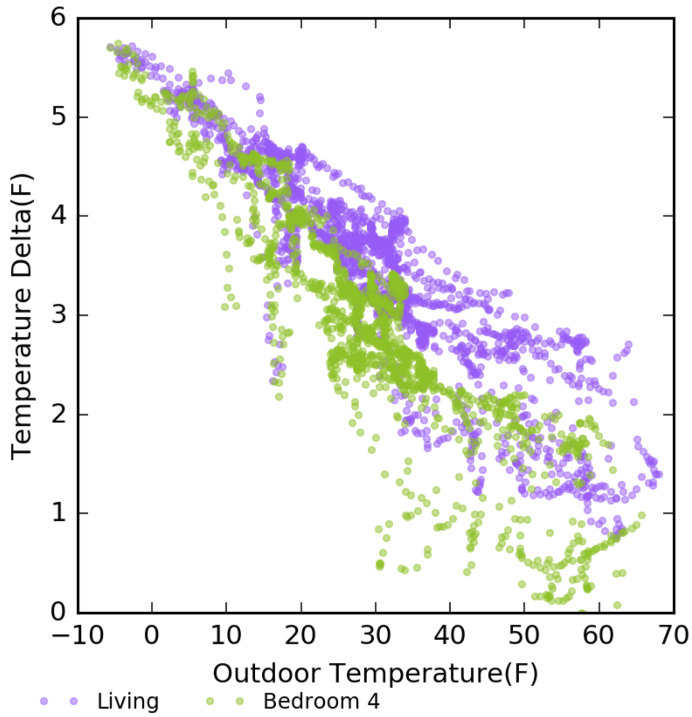


**Figure 45. Floor-to-ceiling stratification (between 4 and 95 in.) compared to outdoor temperature**

### 4.3 Comparison of Model to Measured Data

Zone temperatures predicted by the simulation were compared to measured data for a 2-day period with conditions in a fixed state in the home. Information about the instrumentation and measurements of the lab home are detailed in the previous Section 4.2.2 Unoccupied Test House Measurement Methods. Time constraints prohibited a more robust comparison to more operational states and seasons; however, the team felt that a basic confirmation was all that was necessary. The team wanted to confirm that the model was able to reasonably predict the same room-to-room stratification in the home. A small set of simulations were run with variable parameters, and the combination that yielded the closest results was chosen as the configuration to use in the system comparison analysis.

One aspect of the PnP system that was not accounted for by the AFN easily was the plenum box's effect on airflow balancing. In combination with the plenum geometry's effects on balancing, uncertainty in the losses caused by fittings and the duct segment lengths contributed further differences between the predicted simulation airflows from each duct and the measured flows in the lab house. Therefore, to compare the simulated airflow volumes to measured quantities, short segments of ducts were added to each runout directly after the plenum to add additional airflow resistance—simulating balancing dampers to account for the plenum box's effect on balancing. These segments were identical to a duct segment but with a high loss coefficient value to increase the pressure. The purpose was not to balance to design loads but to account for the plenum box's effects. Table 27 summarizes the balancing results compared to the measured values.

The plenum box effects would be variable depending on the AHU and box geometry, but the lengths of the runouts themselves seemed to far outweigh the box effects because there was generally good agreement without balancing. Additionally, designing a manifold for equal pressure at each outlet was not part of this research. Therefore, balancing was not included in the models used for analysis to account for the plenum box, assuming a plenum box could be designed that would have minimal impact on air distribution.

**Table 27. Measured versus Modeled Airflows, Balanced and Unbalanced (CFM)**

| Zone | Measured Airflow | Modeled Airflow—Unbalanced | Difference Unbalanced | Modeled Airflow—Balanced | Difference Balanced | % Difference Balanced |
|---|---|---|---|---|---|---|
| Bedroom 2 | 13.7 ± 0.4 | 11.8 | -1.9 | 13.3 | -0.4 | -3.1% |
| Bedroom 3 | 11.9 ± 0.4 | 10.9 | -1.0 | 12.2 | 0.2 | 1.9% |
| Bedroom 4 | 26.3 ± 0.8 | 24.1 | -2.2 | 26.6 | 0.2 | 0.6% |
| Master Bedroom | 32.1 ± 1.0 | 31.4 | -0.7 | 32.4 | 0.2 | 0.7% |
| Finished Basement | 10.6 ± 0.3 | 9.5 | -1.1 | 10.7 | 0.1 | 0.8% |
| Unfinished Basement | 13.3 ± 0.4 | 12.4 | -0.9 | 13.3 | 0.0 | -0.3% |
| Dining | 13.5 ± 0.4 | 14.5 | 1.0 | 13.6 | 0.0 | -0.1% |
| Foyer | 18.3 ± 0.5 | 23.1 | 4.8 | 17.9 | -0.5 | -2.7% |
| Kitchen | 13.7 ± 0.4 | 15.1 | 1.4 | 13.9 | 0.2 | 1.5% |
| Living | 16.8 ± 0.5 | 17.3 | 0.5 | 16.9 | 0.1 | 0.3% |

The monitored home had 2-in. ducts installed, and the team ran a series of models to determine an appropriate U-factor to use in the runout ducts. Table 28 documents the final supply air temperatures as modeled and compared to the measured values. These values were taken after the simulation had operated with the fan and furnace at a steady state for 90 min. The temperatures presented in the table correspond to airflows balanced to match the measured airflows shown in Table 28.

**Table 28. Comparison of Measured and Modeled Supply Air Temperatures**

| Zone Outlet | Measured | Modeled | dT |
|---|---|---|---|
| Foyer | 98.7 | 100.0 | -1.3 |
| Dining | 89.3 | 87.5 | 1.9 |
| Bedroom 2 | 78.1 | 77.2 | 0.9 |
| Unfinished Basement | 81.4 | 80.9 | 0.6 |
| Bedroom 4A | 83.2 | 78.3 | 4.9 |
| Bedroom 4B | 83.2 | 79.4 | 3.8 |
| Bedroom 3 | 72.0 | 73.5 | -1.5 |
| Kitchen | 89.8 | 88.3 | 1.5 |
| Living | 92.8 | 93.5 | -0.7 |
| Master Bedroom A | 83.2 | 86.1 | -2.9 |
| Master Bedroom B | 83.2 | 87.5 | -4.3 |

A comparison of the output calculated room-to-room temperature differences for the 2-day period showed that the model very closely matched the measured data for the first day. Figure 46 details the model overlaid with the measured values. The second day results in the afternoon indicate a solar-driven discrepancy. Two culprits were discussed: shading effects of surrounding context and the weather file. Although the surrounding context was not included to shade the home, the nearest homes would not have had a significant impact on solar gains.

It was determined that the error was likely caused by an incomplete weather file. Global horizontal radiation data were measured at the site; however, individual components of the radiation source were not measured (beam, diffuse, direct). The modified weather file did not include these additional radiation components. The lab house simulation might have been made to more closely match measured data if these additional components had been measured, but this was not done in the interest of time.

The coefficient of variance of the root mean square error was used to evaluate the goodness of fit of the simulation to the instrumented home for a short period. Equation (9) describes the metric:

$$CVRMSE = \frac{\sqrt{\sum \frac{(y_i - \hat{y}_i)^2}{n}}}{\bar{y}} \tag{9}$$

where:

$n$ = number of observations

$y_i$ = measured temperature

$\hat{y}_i$ = simulated temperature

$\bar{y}_i$ = mean of all measured temperatures.

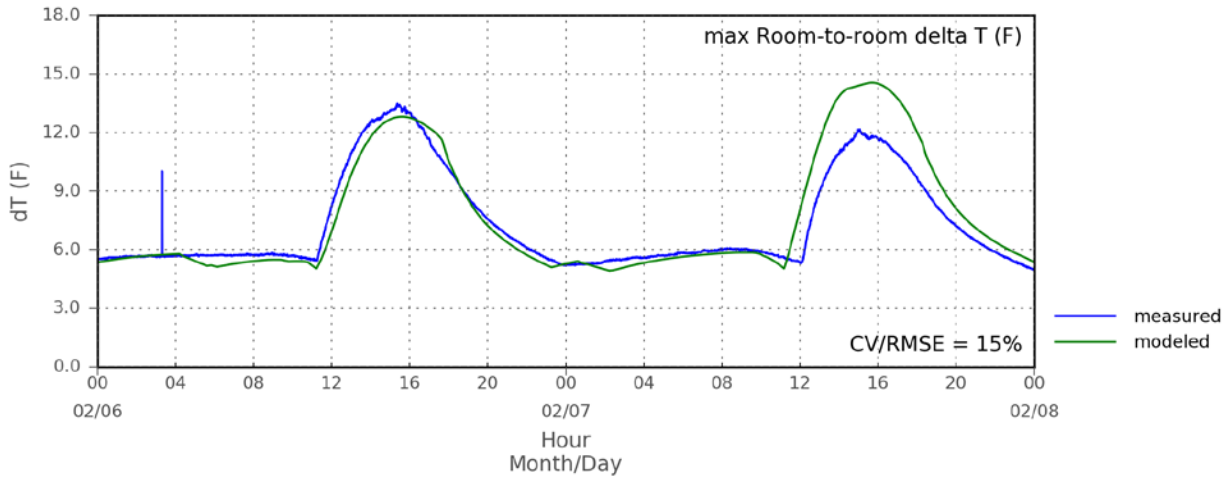


**Figure 46. Modeled versus measured room-to-room max temperature delta**

Figure 47 and Figure 48 show the modeled versus measured zone air temperatures for each zone. The coefficient of variance of the root mean square error is shown for each zone. Many zones show quite good correlation to measured data. One obvious difference in the data is that the simulation shows more frequent system cycling, whereas the measured data showed more constant zone temperatures. At the time the measured data were collected, it was expected that a variable-speed fan could be used with the AFN because that is what was installed and running in the home.

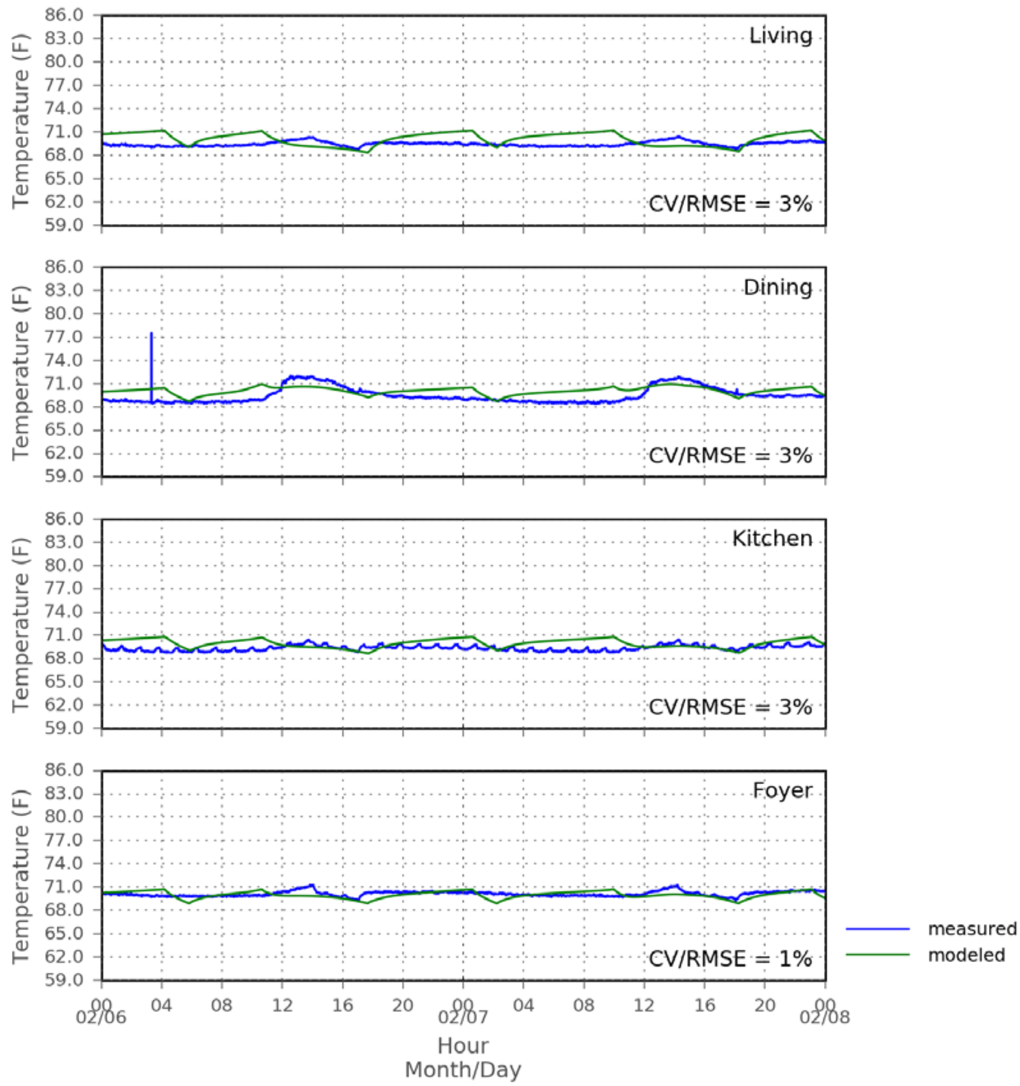


**Figure 47. Modeled versus measured zone air temperatures, first floor**

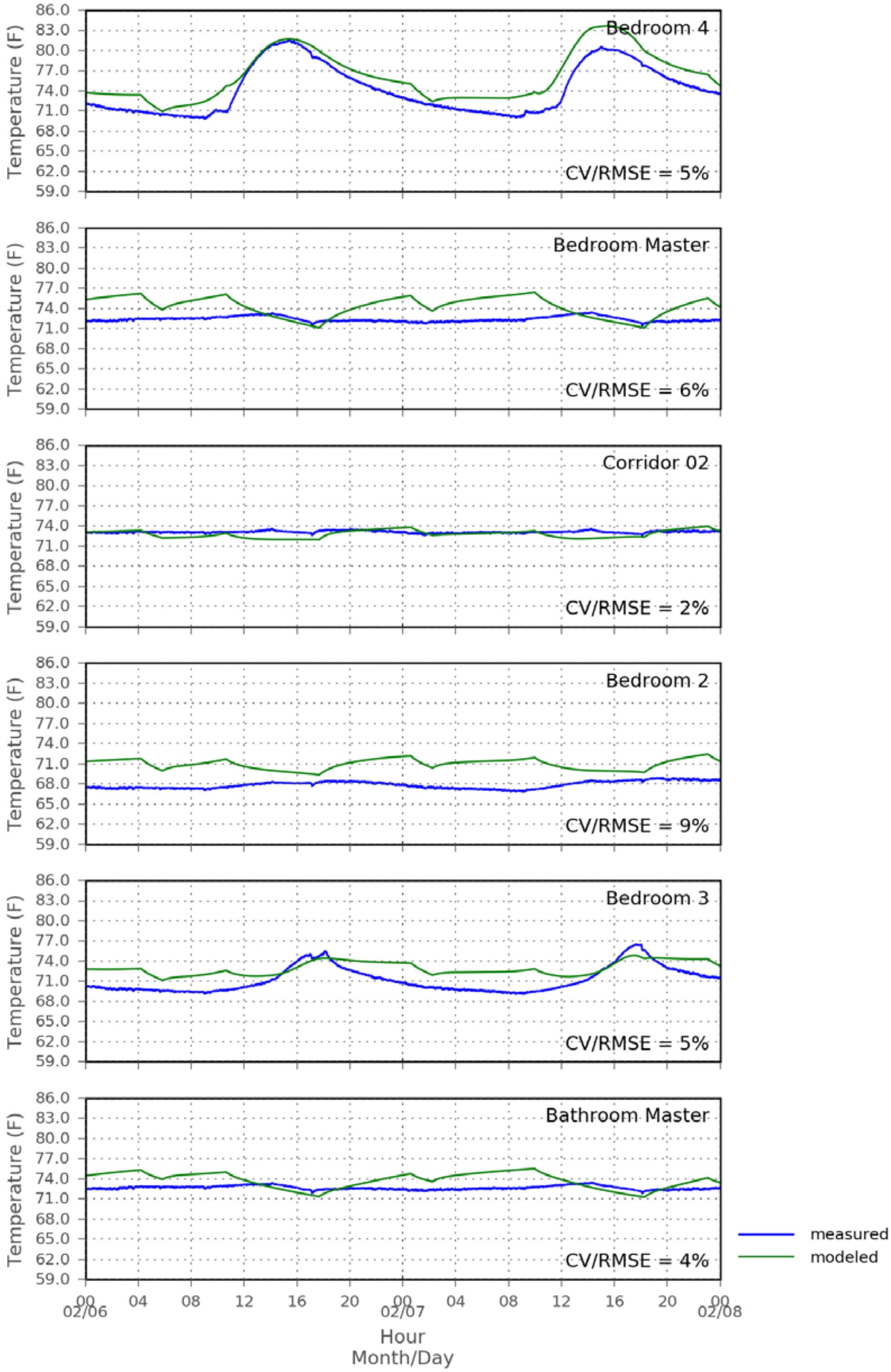


**Figure 48. Modeled versus measured zone air temperatures, second floor**

## 4.4 Results

### *4.4.1 Design Methodology Evaluation*

The team completed an analysis of four design methodologies to select one that yielded the best performance in terms of temperature uniformity. Ultimately, the simulation results alone did not reveal a conclusive winner among the design candidates. Differences in seasonal loads resulted in some zones being over- or under-conditioned. Design Method 3 was selected for relative accuracy, simplicity, and reproducibility.

A complete description of each design method can be found in Performance Evaluation (Section 4).

The design method approaches were evaluated subjectively as well as quantitatively using the thermal simulations. Each design method candidate was entered into the model by modifying the number of duct runs to each conditioned zone to match the design. Table 29 shows the flow to each zone as predicted by the AFN. Table 30 shows the number of duct and supply drops into each indicated room in light grey text. The impact of the changes to the number of ducts can be seen. In Climate Zone 3, the additional airflow going to the second floor with design methods 2, 3, and 4 showed an improvement in the summer cooling. In Climate Zone 3, design methods 2, 3, and 4 each resulted in the same design, also increasing the airflow to the second-floor bedrooms. In Climate Zone 5, the bedrooms each received an extra duct with Design Method 4. This resulted in additional excess air to the top floor, and it pushed the average temperature difference between rooms past 10°F. In the case of Climate Zone 5, Design Method 3, several ducts on the first floor were removed, which resulted in more air going to the top floor. Again, this exacerbated an already excessive amount of air going to this floor in the heating season. Summer performance in Climate Zone 5 was improved by these additional ducts. Note that these airflows are significantly higher than the lab home test case because of the differences in enclosure insulation levels and airtightness.

**Table 29. Zone Total Airflow (CFM) and Number of Ducts Predicted by Simulation**

| Climate Zone | 2 | | | | 3 | | | | 5 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Design Method** | **1** | **2** | **3** | **4** | **1** | **2** | **3** | **4** | **1** | **2** | **3** | **4** |
| Master bathroom | 60 1 | 49 1 | 52 1 | 49 1 | 60 1 | 50 1 | 50 1 | 50 1 | 41 1 | 41 1 | 52 1 | 40 1 |
| Bedroom 2 | 48 1 | 39 1 | 41 1 | 39 1 | 48 1 | 39 1 | 39 1 | 39 1 | 33 1 | 32 1 | 41 1 | 63 2 |
| Bedroom 3 | 45 1 | 73 2 | 77 2 | 73 2 | 45 1 | 74 2 | 74 2 | 74 2 | 61 2 | 60 2 | 77 2 | 89 3 |
| Bedroom 4 | 49 1 | 80 2 | 84 2 | 80 2 | 50 1 | 81 2 | 81 2 | 81 2 | 67 2 | 66 2 | 84 2 | 97 3 |
| Master bedroom | 60 1 | 49 1 | 52 1 | 49 1 | 61 1 | 50 1 | 50 1 | 50 1 | 83 2 | 81 2 | 52 1 | 40 1 |
| Finished basement | 41 1 | 66 2 | 35 1 | 66 2 | 41 1 | 67 2 | 67 2 | 67 2 | 55 2 | 81 3 | 69 2 | 80 3 |
| Unfinished basement | 51 1 | 42 1 | 45 1 | 42 1 | 52 1 | 43 1 | 43 1 | 43 1 | 70 2 | 69 2 | 88 2 | 68 2 |
| Dining | 57 1 | 46 1 | 49 1 | 46 1 | 57 1 | 47 1 | 47 1 | 47 1 | 39 1 | 38 1 | 49 1 | 37 1 |
| Foyer | 79 1 | 65 1 | 69 1 | 65 1 | 80 1 | 66 1 | 66 1 | 66 1 | 110 2 | 54 1 | 69 1 | 53 1 |
| Kitchen | 58 1 | 48 1 | 50 1 | 48 1 | 59 1 | 48 1 | 48 1 | 48 1 | 40 1 | 78 2 | 50 1 | 77 2 |
| Living | 64 1 | 53 1 | 56 1 | 53 1 | 65 1 | 53 1 | 53 1 | 53 1 | 89 2 | 87 2 | 56 1 | 43 1 |
| *Total flow* | *617 11* | *616 14* | *616 13* | *616 14* | *622 11* | *622 14* | *622 14* | *622 14* | *690 18* | *691 19* | *691 15* | *691 20* |

In Climate Zone 2, the designs were very similar. Design Method 1 had fewer ducts to the top floor because it did not account for differences in duct lengths. A similar design also resulted for Climate Zone 3. In Climate Zone 5, there is a noticeable difference among the different approaches. This is largely because many of the zones were midway between receiving one or two ducts. Design Method 3 resulted in fewer ducts to many of the zones. Design Method 4, which also accounts for temperature loss, required more ducts in some zones.

Thermal simulations were used to evaluate the design methods so that the impact on comfort of adding or removing a duct could be quantified. Table 30 summarizes these results. The model showed the house within acceptable limits (4°F during the winter and 6°F during the summer), in climate zones 2 and 3 most the time. In Climate Zone 5, the air delivery system struggled to maintain comfort. In the winter, the top floor of the house received too much airflow, and it was over-conditioned. This resulted in a high average temperature difference among zones. In the summer, the top floor also remained warm in Climate Zone 5. System operation helped reduce the stratification; however, because of the mild climate, the thermostat on the bottom floor did not call for cooling frequently.

**Table 30. Average Room-to-Room Temperature for Each Design Method**

| | Summer | | | | Winter | | | |
|---|---|---|---|---|---|---|---|---|
| Design Method | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Climate Zone2 | 2.1 | 1.5 | 1.5 | 1.5 | 3.1 | 3.4 | 3.7 | 3.4 |
| Climate Zone 3 | 3.1 | 1.9 | 1.9 | 1.9 | 4.8 | 5.4 | 5.4 | 5.4 |
| Climate Zone 5 | 5.2 | 5.2 | 4.9 | 4.8 | 8.7 | 8.8 | 9.4 | 10.8 |

Although the mean is useful for a simple comparison, the distributions were also analyzed to see the results from a different perspective. Figure 49 shows the temperature uniformity distributions for each of the four design methods for each climate zone and season. As illustrated by the mean values, there is little difference among the best performing methods, with Design Method 3 showing more consistent results.

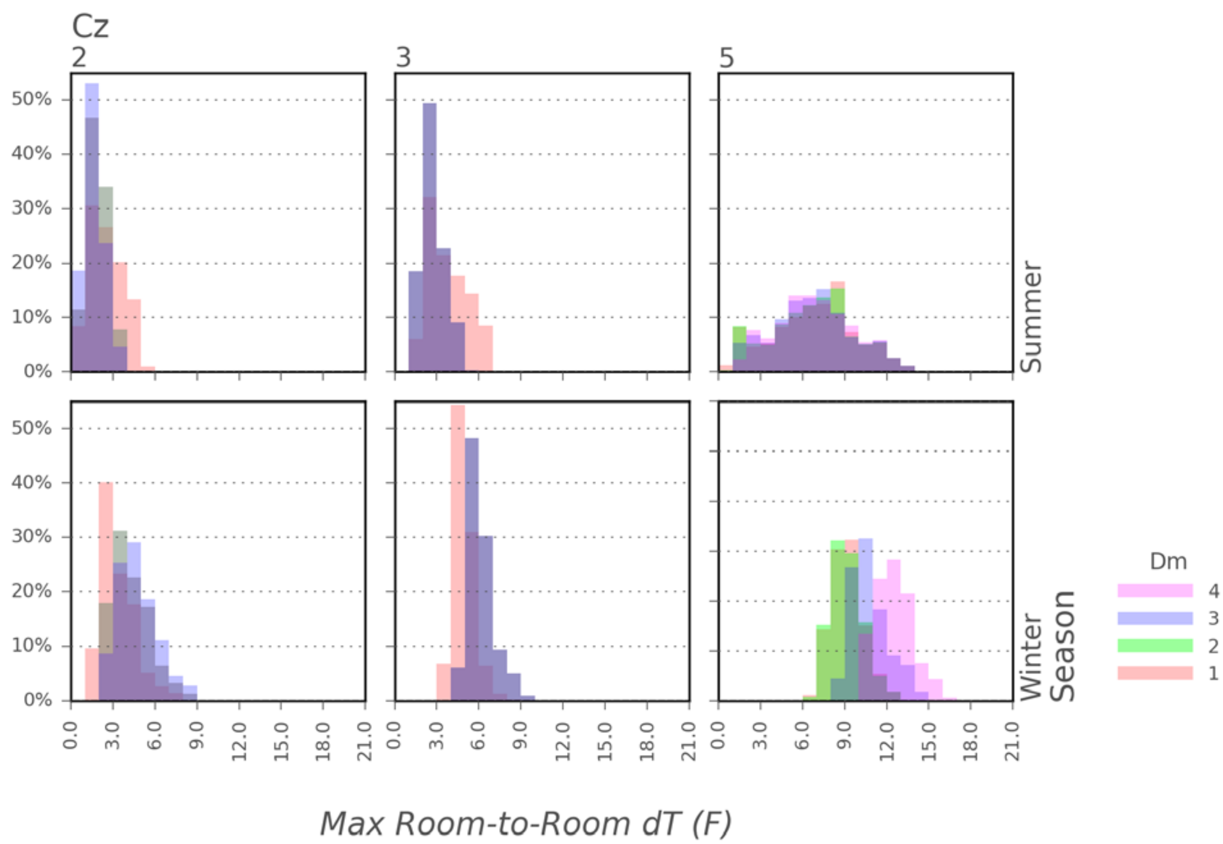


**Figure 49. Comparison of design method temperature uniformity**

Table 31 shows the load and airflow requirements for each zone. Loads have been calculated using Wrightsoft for each climate zone. The required heating and cooling airflow is shown, along with the actual airflow predicted by the design method. The percentage difference is shown. A major challenge when designing HVAC systems is the difference in airflow requirements in heating and in cooling. A system that does not have the ability to be rebalanced at the beginning of each season will provide compromised comfort. The simulation results show this outcome. Another challenge when designing systems is in deciding when a zone's load is small enough that it does not warrant a dedicated duct run. The master bathroom is one such zone. As a result, this zone tends to be over-conditioned in both seasons. Western-facing Bedroom 4, which has a significantly higher cooling design load, receives excess air in the winter.

Table 31. Loads and Airflow Required for Each Zone and Design Method 3 Airflow

| | | H-Btuh | C-Btuh | Heating | | Cooling | | Design Method 3 Predicted |
|---|---|---|---|---|---|---|---|---|
| | | | | CFM[a] | | CFM[a] | | CFM |
| 2 | Breakfast | 1,353 | 963 | 31 | 28% | 26 | 56% | 40 |
| | Dining | 1,213 | 972 | 28 | 43% | 26 | 53% | 40 |
| | Family | 2,113 | 1,547 | 49 | 15% | 41 | 36% | 56 |
| | Foyer | 1,503 | 993 | 35 | 93% | 27 | 152% | 67 |
| | Bedroom 2 | 1,295 | 1,304 | 30 | 13% | 35 | -3% | 34 |
| | Bedroom 3 | 875 | 1,958 | 20 | 211% | 52 | 20% | 63 |
| | Bedroom 4 | 1,813 | 1,847 | 42 | 56% | 49 | 32% | 65 |
| | Master bedroom | 1,860 | 1,850 | 43 | 12% | 50 | -3% | 48 |
| | Master bathroom | 778 | 653 | 18 | 155% | 18 | 162% | 46 |
| | | | | | | | | |
| 3 | Breakfast | 1,417 | 975 | 33 | 23% | 26 | 54% | 40 |
| | Dining | 986 | 916 | 23 | 76% | 25 | 63% | 40 |
| | Family | 1,846 | 1,331 | 43 | 32% | 36 | 58% | 56 |
| | Foyer | 1,412 | 851 | 33 | 106% | 23 | 194% | 67 |
| | Bedroom 2 | 1,148 | 1,126 | 27 | 28% | 30 | 12% | 34 |
| | Bedroom 3 | 744 | 1,889 | 17 | 266% | 51 | 24% | 63 |
| | Bedroom 4 | 1,620 | 1,836 | 37 | 75% | 49 | 33% | 65 |
| | Master bedroom | 1,768 | 1,689 | 41 | 18% | 45 | 7% | 48 |
| | Master | 575 | 389 | 13 | 245% | 1 | 339 | 46 |

| | | H-Btuh | C-Btuh | Heating | | Cooling | | Design Method 3 Predicted |
|---|---|---|---|---|---|---|---|---|
| | bathroom | | | | | 0 | % | |
| | | | | | | | | |
| 5 | Breakfast | 2,519 | 705 | 58 | -31% | 19 | 112% | 40 |
| | Dining | 1,749 | 976 | 40 | -1% | 26 | 53% | 40 |
| | Family | 3,267 | 991 | 75 | -25% | 27 | 112% | 56 |
| | Foyer | 2,653 | 510 | 61 | 9% | 14 | 391% | 67 |
| | Bedroom 2 | 1,983 | 839 | 46 | -26% | 22 | 51% | 34 |
| | Bedroom 3 | 1,249 | 2,303 | 29 | 118% | 62 | 2% | 63 |
| | Bedroom 4 | 2,808 | 1,829 | 65 | 1% | 49 | 34% | 65 |
| | Master bedroom | 3,033 | 1,229 | 70 | -31% | 33 | 47% | 48 |
| | Master bathroom | 1,018 | 229 | 24 | 95% | 6 | 646% | 46 |

* Represents the percentage of *Manual J* design airflow predicted by the duct design method

### 4.4.2 System Comparison

A primary task of this research was a comparison of a trunk-and-branch duct layout using flex duct runouts from a rigid metal trunk to the PnP system. The trunk-and-branch system was considered the best comparison because of its prevalence in new production homes. The research team wanted to understand how the layout and materials would affect the air balancing of a system and simulate the resultant temperature uniformity of the home. The team was interested in determining whether an unbalanced PnP strategy that varied zone airflows through a simple integer number of ducts mechanism could provide uniformity comparable to what is experienced commonly in homes.

As a benchmark, based on a past IBACOS research project, data collected from 27 homes in a hot and humid climate showed that the maximum room-to-room temperature difference was less than 6°F 95% of the time. These data were collected during late summer from homes built between 2014 and 2015 to the Environments for Living program standard. Similar performance was observed in the simulated house during the summer period.

Simulations were designed to be able to compare the system configurations with varying inputs, such as trunk-and-branch to PnP layouts and doors open to doors closed. Simulated temperatures were analyzed as to the resulting overall uniformity of the home—the maximum room-to-room temperature difference. A combination of histogram charts and tables are used to describe the differences among subsets of models. The charts in this section contain the aggregate room-to-room temperature difference histograms showing the percentage of time model zones spent in one-degree bins. Chart facets contain pairs of models overlaid to show the difference between the two systems.

The sensitivity of temperature uniformity to individual significant parameters was assessed. Table 32 describes the variables and their values used for comparison. High and low values were input to illustrate realistic boundary operating scenarios that occur in typical installed systems. The comparisons were designed to get a sense of how the variations of these parameters impact temperature uniformity. The model components and their individual effects were detailed in 4.1Modeling Methods (Section 4.1).

**Table 32. Simulation Comparison Scenarios**

| Parameter | Scenarios (Value) | |
|---|---|---|
| Systems | Trunk-and-Branch | PnP |
| Duct roughness | Smooth<br>(0.000015 m) | Compressed<br>(0.015 m) |
| Duct U-factor | Uninsulated<br>(5.74 W/m2 K) | Insulated<br>(2.15 W/m$^2$ K) |
| Internal gains | On | Off |
| Duct leakage | Low<br>(<1% of system flow) | High<br>(~20% of system flow) |
| Interior doors | Open<br>(1.0) | Closed<br>(0.1) |

To compare the trunk-and-branch system to the PnP, simulations were run with the doors closed and with each system's duct parameters set to values that would be expected to result in reduced temperature uniformity—i.e., a challenging case. Figure 50 illustrates the results of the challenging case. In all climate zones and both seasons, the PnP system performs more consistently and was in ACCA uniformity limits for between 2% and 42% more than the trunk-and-branch system. During the winter, although both performed poorly because of a lack of seasonal balancing, the PnP system had a consistently lower maximum room-to-room temperature difference. In other words, the PnP performed more consistently.

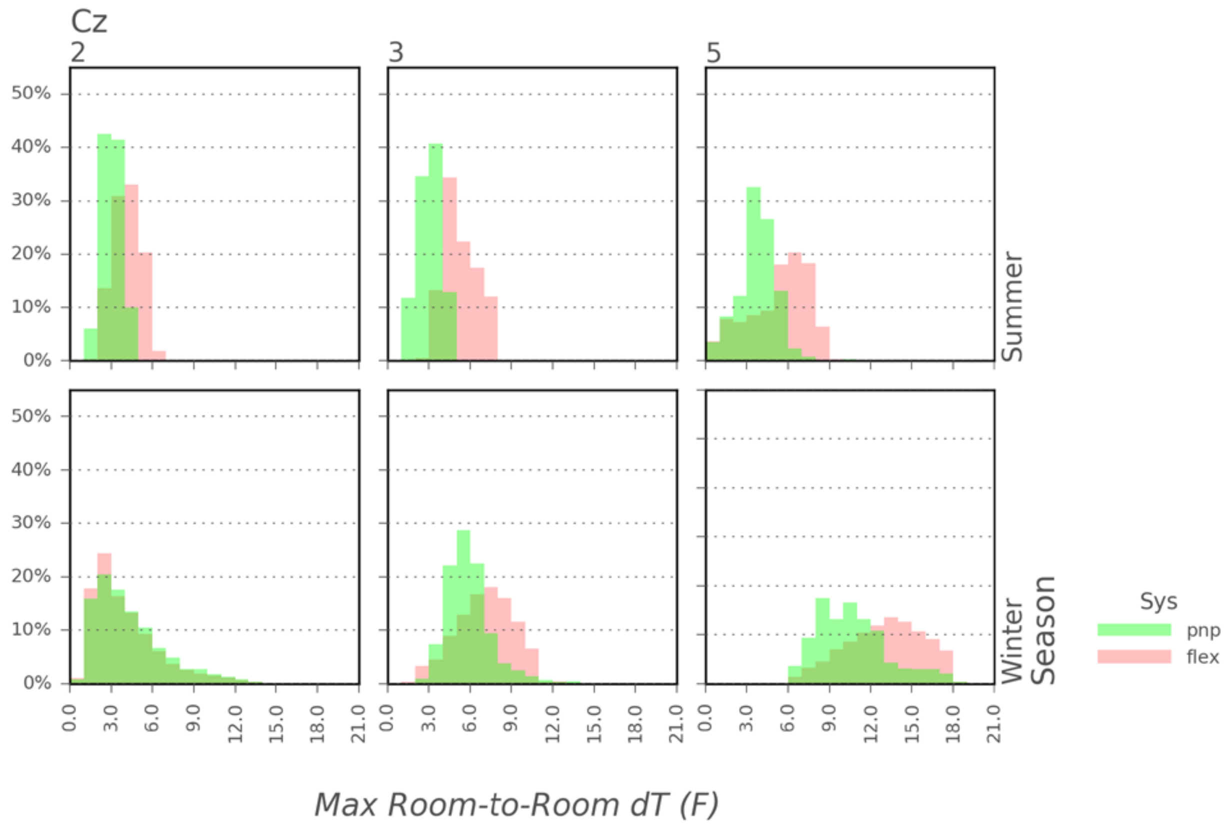


**Figure 50. System comparison, challenging case**

**Table 33. System Performance, Challenging Case**

| Season | | | Summer | | Winter | |
|---|---|---|---|---|---|---|
| System | | | Traditional | PnP | Traditional | PnP |
| Climate Zone | 2 | *dT (F) Max* | 4.1 | 3.0 | 4.0 | 4.3 |
| | | *stdev* | 1.0 | 0.7 | 2.4 | 2.5 |
| | | *% Passing ACCA* | 98% | 100% | 60% | 55% |
| | 3 | *dT (F) Max* | 5.3 | 3.1 | 7.1 | 5.9 |
| | | *stdev* | 1.2 | 0.8 | 2.1 | 1.6 |
| | | *% Passing ACCA* | 71% | 100% | 8% | 8% |
| | 5 | *dT (F) Max* | 5.3 | 3.8 | 13.0 | 10.7 |
| | | *stdev* | 2.2 | 1.4 | 2.8 | 2.6 |
| | | *% Passing ACCA* | 54% | 96% | 0% | 0% |

In addition to the challenging case, another case looks at an easier condition represented by the doors opened and duct parameters representing better installation quality such as tighter air sealing and lower flex duct roughness. In all cases, the PnP performed as good or better. Both systems performed poorly where seasonal balancing adjustments would be advised and when the cooling load was comparable to the heating load. This is the case in the winter season in the colder two climates and during both seasons in the mixed climate with strong heating and cooling loads, Table 34 documents the summary metrics of the plot, and Figure 51 visualizes the temperature distributions for each model.

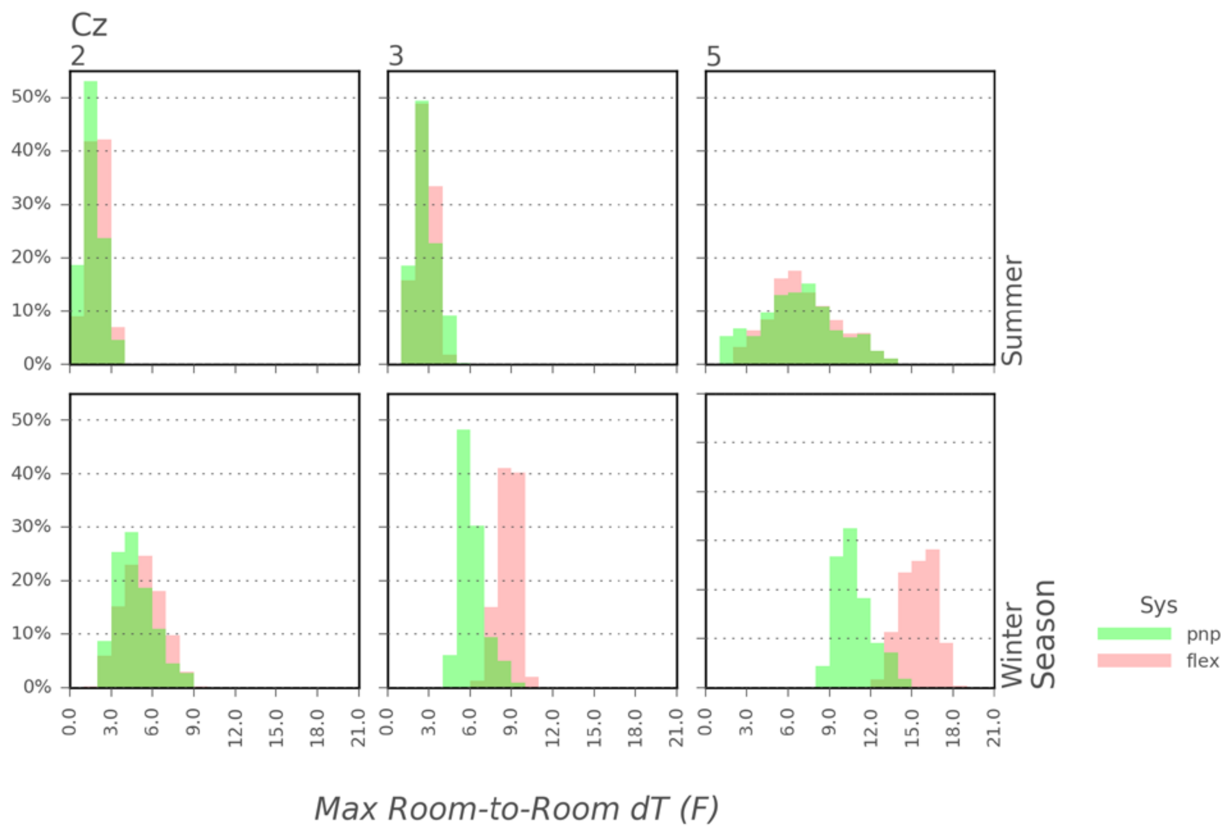


**Figure 51. System comparison, simple case**

**Table 34. System Performance Comparison, Simple Case**

| Season | | | Summer | | Winter | |
|---|---|---|---|---|---|---|
| System | | | Traditional | PnP | Traditional | PnP |
| Climate Zone | 2 | *dT (F) Max* | 2.0 | 1.7 | 5.2 | 4.7 |
| | | *stdev* | 0.7 | 0.7 | 1.5 | 1.4 |
| | | *% Passing ACCA* | 100% | 100% | 21% | 34% |
| | 3 | *dT (F) Max* | 2.7 | 2.7 | 8.8 | 6.1 |
| | | *stdev* | 0.7 | 0.8 | 0.7 | 0.9 |
| | | *% Passing ACCA* | 100% | 100% | 0% | 0% |
| | 5 | *dT (F) Max* | 7.2 | 6.8 | 15.5 | 10.8 |
| | | *stdev* | 2.5 | 2.8 | 1.2 | 1.3 |
| | | *% Passing ACCA* | 34% | 40% | 0% | 0% |

A problem illustrated by both cases' analysis is a lack of seasonal adjustments to the duct balancing, and many if not all excursions beyond acceptable ACCA thresholds for uniformity are because duct systems are not adjusting seasonally. In Climate Zone 5, there is a strong heating load, and the duct design accounting for the large annual swings in load resulted in imperfect uniformity during both winter and summer. For climate zones with primarily a cooling load, this issue is prevalent only in the winter because the number of ducts is not determined by the heating load for any room; however, the PnP was more resilient to the seasonal differences while not completely resolving the issue. In all cases, the PnP distribution performed as well or better than the trunk-and-branch system.

### 4.4.3 Individual Parameter Impacts on Temperature Uniformity

The following sections summarize the impacts of each of the five parameters. Some, such as leakage, are pertinent only for the trunk-and-branch system. Others, such as internal gains, impact both systems equally. Unless otherwise noted, all plots represent the PnP system.

#### 4.4.3.1 Duct U-Factor

Figure 52 illustrates the differences in temperature uniformity because of the ducts' U-value. Initially, the team thought that U-value would have a significant impact on room-to-room uniformity; however, the impacts on the aggregate distribution of room-to-room temperatures of this parameter were negligible except for in Climate Zone 5 in the winter. The scenario with greater conductivity resulted in better winter comfort because more of the heat was lost along the length of the duct (and into other parts of the house) instead of ending up in the conditioned zone.

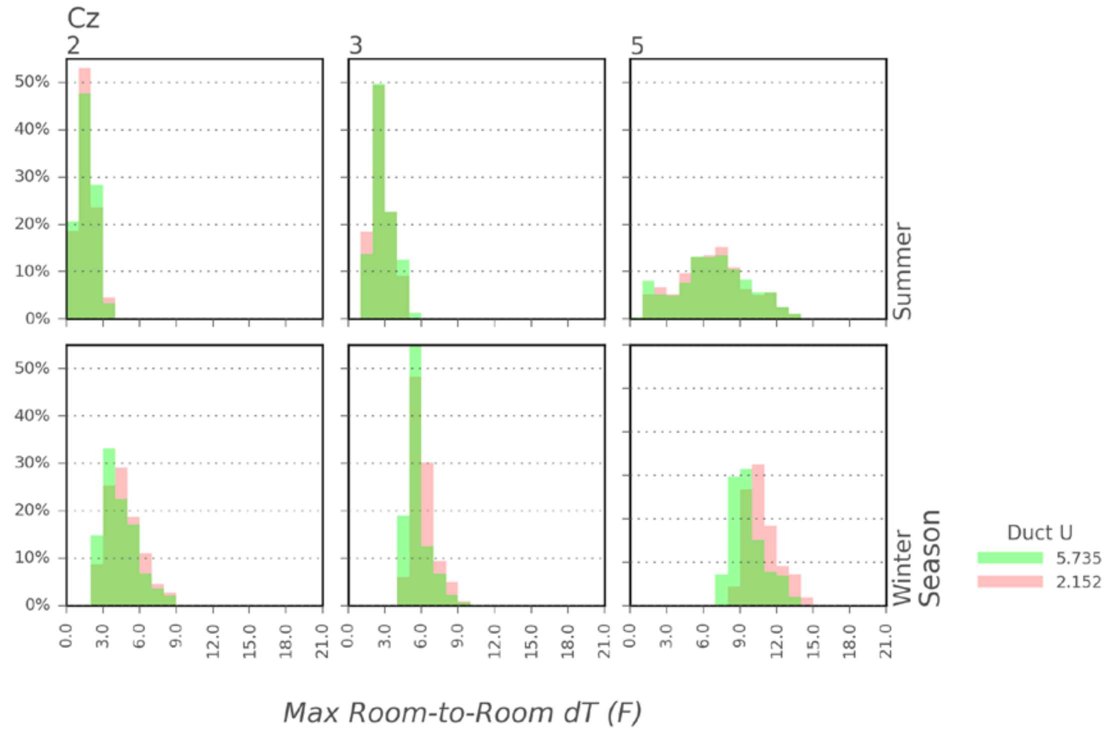


**Figure 52. Density of room-to-room temperature differences affected by duct U-factor**

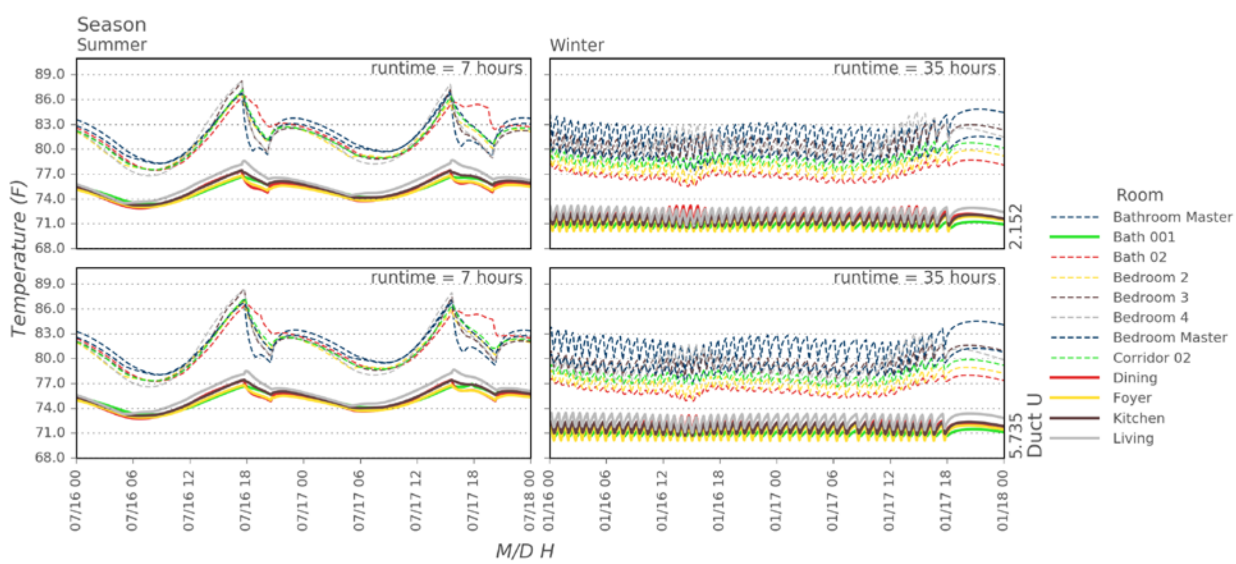


**Figure 53. Room temperature differences affected by duct U-factor**

### *4.4.3.2 Interior Doors*

Past IBACOS research has determined that the passive transfer of air between directly-conditioned spaces and passively conditioned spaces is only adequate to provide space conditioning when doors are open and that ducts should be run to each primary occupied space in a home for acceptable levels of temperature uniformity.

Figure 54 illustrates the impact of door state (open or closed) on temperature uniformity. In all cases except Climate Zone 5 during summer, the temperature uniformity was improved by opening doors. Climate Zone 5 showed better uniformity with the doors closed in summer, which is irregular from the other warmer climate zones. The reason for this is primarily because of the lack of rebalancing the system between seasons to match design airflows. The second floor in the Climate Zone 5 models were receiving too little air in the summer, and with the doors closed less warm air from the first floor was rising and impacting the room air temperatures. If the system were balanced seasonally—as would be recommended, especially in climate zones with equally strong heating and cooling loads—the door opening state would be expected to have the same detrimental effect on overall uniformity.

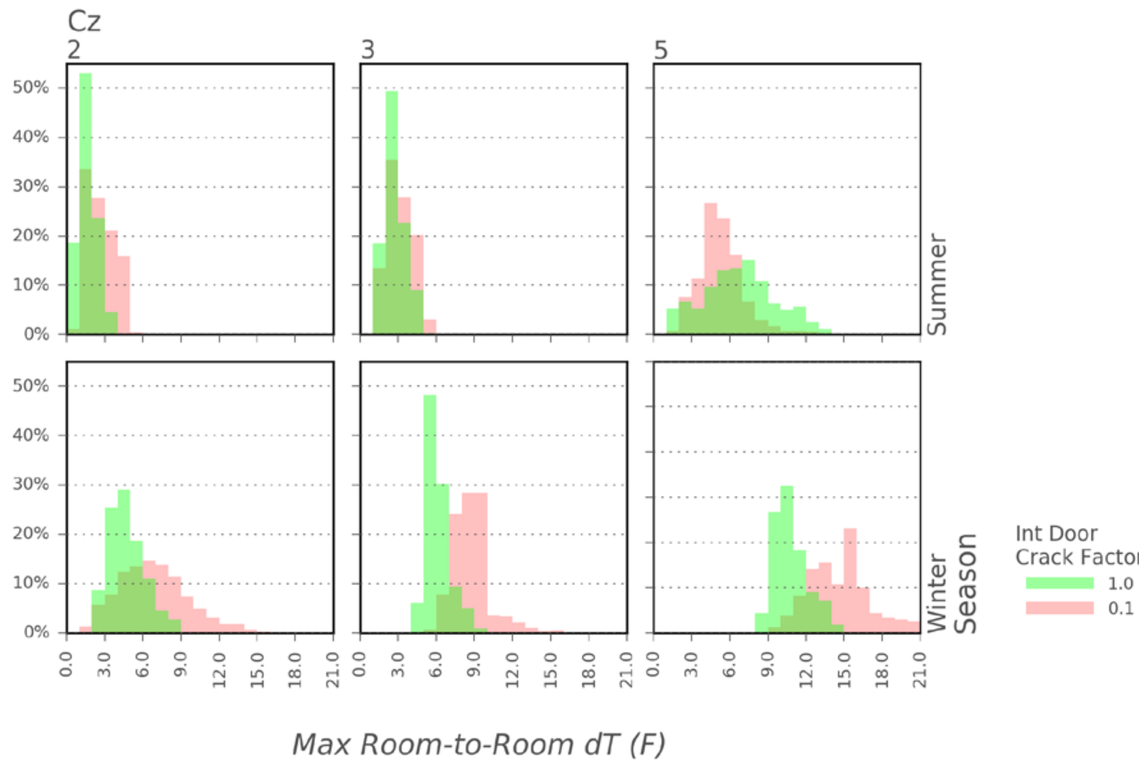


**Figure 54. Density of room-to-room temperature differences affected by door state (PnP)**

### *4.4.3.3 Internal Gains*

Figure 55 shows the differences in temperature uniformity because of the internal gains for the PnP system for each climate zone and season. Their effect is particularly strong in situations when balancing is poor relative to the loads, which in this case is the winter. Cycling in a poorly balanced configuration will lead to worse temperature uniformity, and the internal gains will reduce the load in the winter and visa-versa in the summer, thus shortening and lengthening system run times. Thus, depending on balancing the gains will hurt or hinder the temperature uniformity.

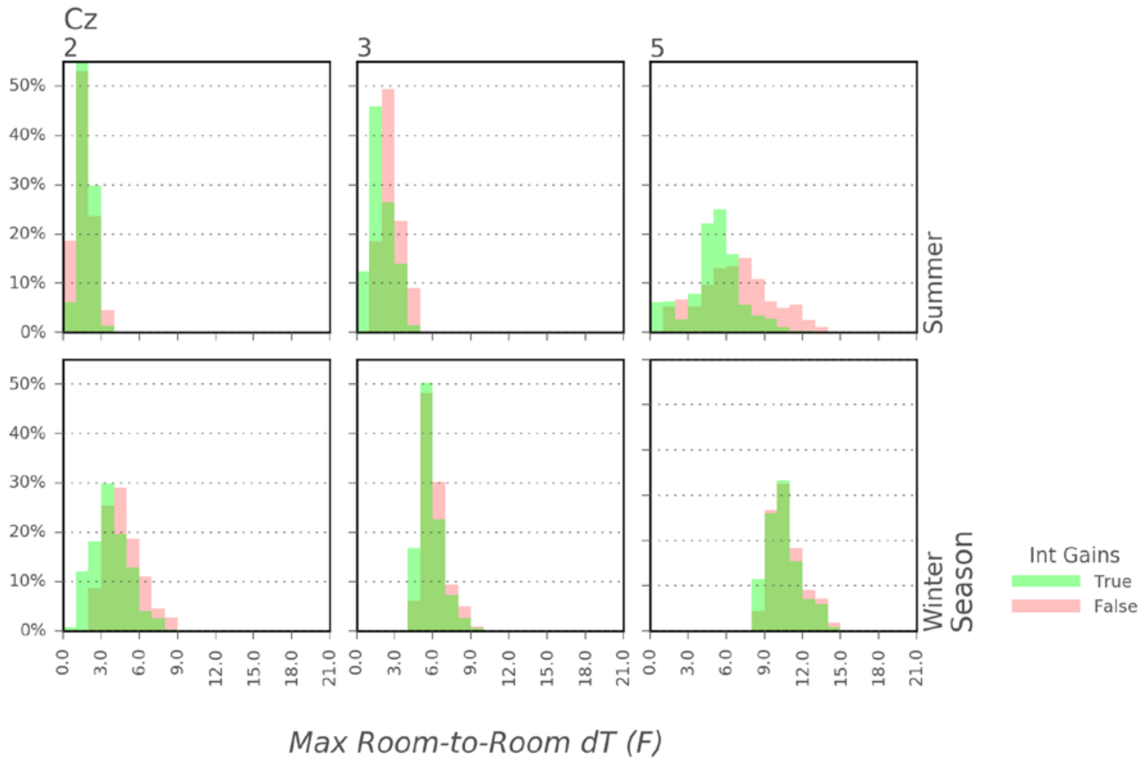


**Figure 55. Density of room-to-room temperature differences affected by internal gains**

Figure 56 shows the effect of system run time for Climate Zone 3 by internal gains—more run time in the winter without internal gains and less with; more run time in the summer with internal gains and less without—as expected. The overall impact on temperature uniformity was minimal, except in the bathrooms, where concentrated heat gains temporarily increased the temperature.

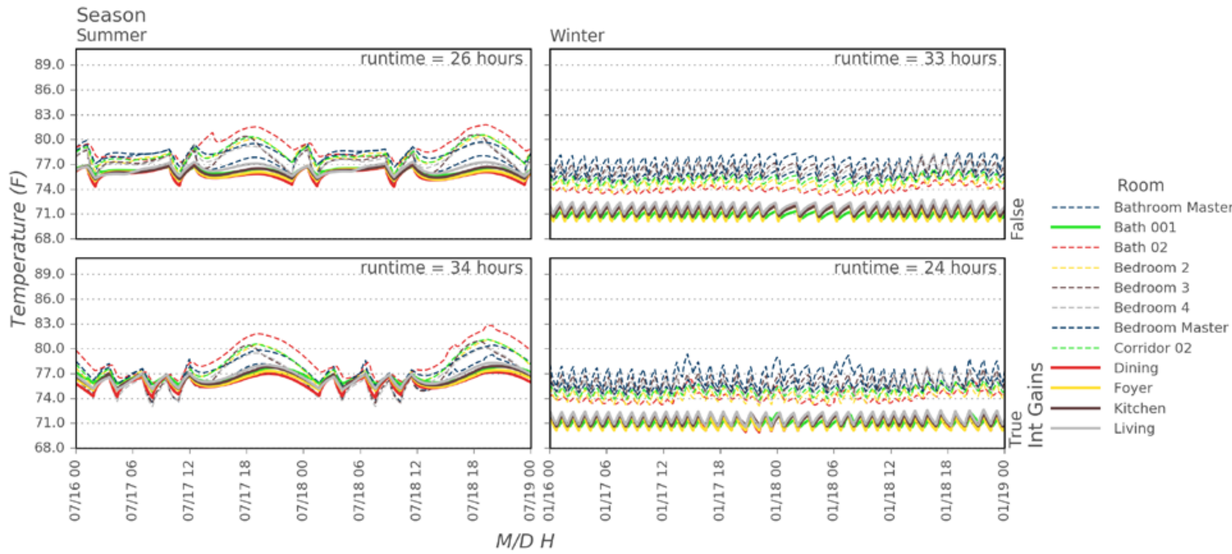


**Figure 56. Room temperature differences affected by internal gains**

### *4.4.3.4 Duct Leakage*

The simulation's predicted room-by-room airflow from the duct system is expected to have the largest impact on uniformity. The trunk-and-branch system was modeled with leakage for each runout (leaks were placed after the branch takeoff). The leakage components exist in the baseline model with flow coefficients of 0.0001, but the resultant leakage is negligible and thus represents a very well-sealed flex duct system. A comparison was made between a higher leakage flex system. Table 35 summarizes the airflows.

**Table 35. Comparison of Trunk-and-Branch System Airflows with Low and High Leakage**

| Flex Duct Roughness (m) | 0.003 | | | | | |
|---|---|---|---|---|---|---|
| Climate Zone | 2 | | 3 | | 5 | |
| Leak Coefficient | 0.0001 | 0.002 | 0.0001 | 0.002 | 0.0001 | 0.002 |
| Master bathroom | 36 | 28 | 34 | 27 | 27 | 21 |
| Bathroom 2 | 22 | 18 | 21 | 17 | 26 | 20 |
| Bedroom 2 | 32 | 20 | 32 | 20 | 33 | 21 |
| Bedroom 3 | 78 | 66 | 104 | 89 | 125 | 102 |
| Bedroom 4 | 78 | 66 | 75 | 63 | 90 | 73 |
| Master bedroom | 68 | 54 | 65 | 52 | 56 | 42 |
| Finished basement | 56 | 45 | 57 | 46 | 55 | 40 |
| Unfinished basement | 35 | 28 | 37 | 30 | 45 | 36 |
| Dining | 47 | 41 | 45 | 37 | 53 | 42 |
| Foyer | 63 | 54 | 60 | 51 | 72 | 58 |
| Kitchen | 34 | 25 | 35 | 27 | 33 | 24 |
| Living | 53 | 40 | 39 | 29 | 55 | 39 |
| Total | 616 | 616 | 622 | 621 | 691 | 688 |
| Standard deviation | 18 | 16 | 22 | 20 | 27 | 23 |
| % Delivered of total leaked | 3% | 21% | 3% | 21% | 3% | 25% |

Figure 57 illustrates the aggregate effect on temperature uniformity associated with differences in duct leakage for the flex duct system. Experience from the field indicates that flex duct systems can have a wide range of leakage amounts, depending on the quality of installation. One advantage of the PnP duct system is that the rigid material and fittings should be less prone to field installation errors.

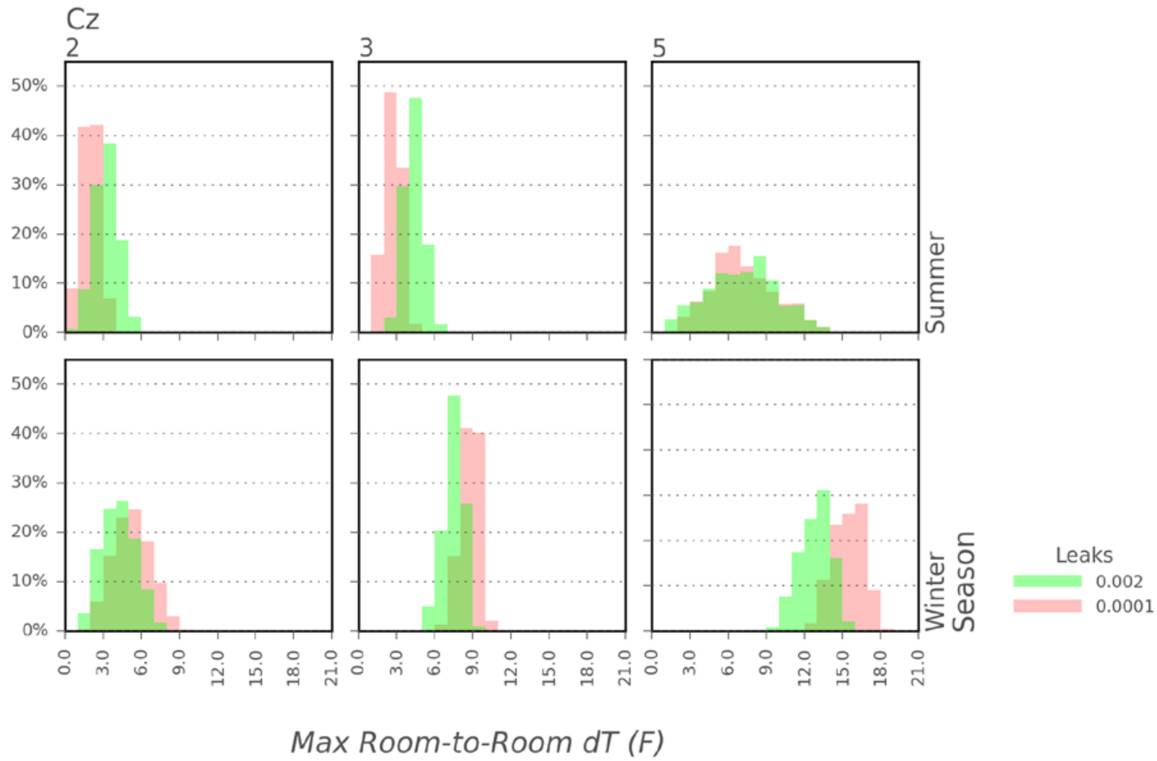


**Figure 57. Effect of duct leakage on temperature uniformity for trunk-and-branch system**

#### *4.4.3.5 Duct Roughness*

A comparison was also made to a higher roughness duct runout, which represents an installation scenario where ducts were not fully stretched. Table 36 documents the differences in air balancing due to uniformly applied duct roughness to all flex runouts, and Figure 58 shows the impact on uniformity. The roughness value of 0.003 m is typical for a well-installed flex duct system (ASHRAE Fundamentals). The roughness value of 0.015 m might be more representative of a poorly installed flex duct system.

**Table 36. Comparison of Trunk-and-Branch System Airflows with Low and High Duct Roughness**

| Climate Zone | 2 | | 3 | | 5 | |
|---|---|---|---|---|---|---|
| Flex Duct Roughness (m) | 0.003 | 0.015 | 0.003 | 0.015 | 0.003 | 0.015 |
| Master bathroom | 36 | 33 | 34 | 31 | 27 | 25 |
| Bathroom 2 | 22 | 19 | 21 | 18 | 26 | 23 |
| Bedroom 2 | 32 | 36 | 32 | 36 | 33 | 34 |
| Bedroom 3 | 78 | 69 | 104 | 94 | 125 | 114 |
| Bedroom 4 | 78 | 70 | 75 | 67 | 90 | 82 |
| Master bedroom | 68 | 63 | 65 | 61 | 56 | 51 |
| Finished basement | 56 | 61 | 57 | 61 | 55 | 57 |
| Unfinished basement | 35 | 36 | 37 | 45 | 45 | 56 |
| Dining | 47 | 46 | 45 | 44 | 53 | 52 |
| Foyer | 63 | 67 | 60 | 65 | 72 | 77 |
| Kitchen | 34 | 37 | 35 | 37 | 33 | 34 |
| Living | 53 | 61 | 39 | 43 | 55 | 60 |
| Total | 616 | 617 | 622 | 622 | 691 | 691 |
| Standard deviation | 18 | 17 | 22 | 19 | 27 | 25 |

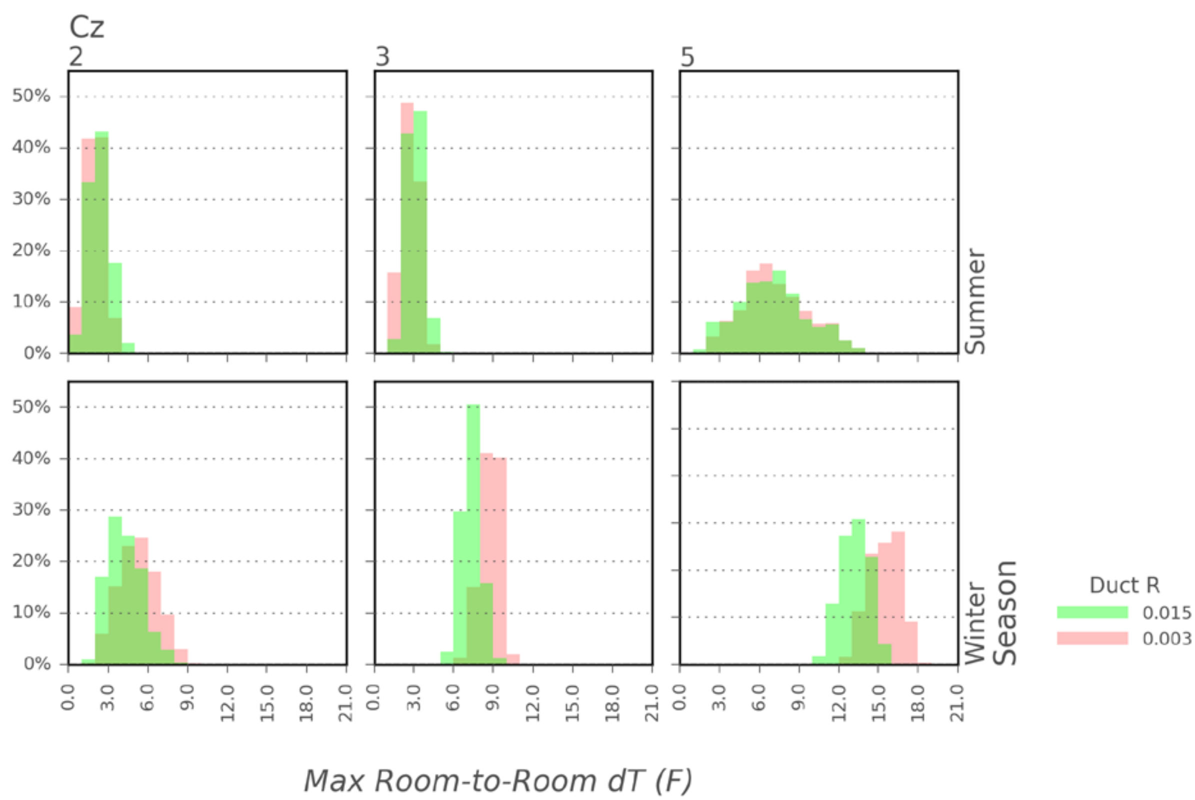


**Figure 58. Impact of duct roughness on temperature uniformity**

# 5 Market Engagement: Results and Discussion

The goal of this project was to develop a simplified residential air delivery system that is a solution to air distribution and comfort delivery issues in low-load production-built homes and is emergent on the industry. Market engagement was one of the primary tasks of this project.

Primary market engagement activities included the following:

- Understanding builder attitudes and values
- Identifying building code obstacles
- Understanding consumer attitudes and values
- Presenting material at industry events
- Securing builder commitment to demonstrate the PnP technology and securing manufacturer commitment to commercialize the technology.

For the PnP system, outcomes of the market engagement activities demonstrated real interest in the technology and highlighted key areas where this technology could help builders improve performance and increase their bottom line. Where codes and regulations are pushing for higher performance and requiring ductwork to be installed inside conditioned space (such as in California's Title 24[5]), the PnP system could be a cost-effective means to achieve these required targets. With reduced labor needed to install and commission the PnP system, builders and their trades can reduce costs while achieving good comfort in their homes. The primary barrier to the development and adoption of the PnP system is the current code barrier around the use of plastic ductwork, which must be addressed before the full potential of this system can be realized.

To gain interest, acceptance, and demand for the PnP air delivery system, IBACOS engaged with industry stakeholders through a variety of means, including the Housing Innovation Alliance (Alliance) working groups, ongoing Alliance activities that incorporate the PnP system, and participation with a variety of industry groups and committees. These market engagement activities were critical to ensure that the PnP system (1) is relevant to the industry, (2) is market feasible, (3) provides a strong market value proposition, and (4) is promoted in the industry. Through these market engagement activities, obstacles and barriers to the implementation of the PnP system were identified, along with possible stakeholders that can overcome these barriers.

Stakeholders identified in this project include U.S. homebuilders, building products manufacturers serving the U.S. housing market, the building codes community (International Code Council, code officials, U.S. Department of Energy), U.S. housing consumers, and industry organizations (e.g., Housing Innovation Alliance, Pennsylvania Housing Research Center) and their membership and audiences.

The outcomes described below were achieved through the completion of these activities.

[5] http://www.energy.ca.gov/title24/

## 5.1 Builder Attitudes and Values

IBACOS engaged with several national and regional homebuilders to present the PnP system strategy and cost and installation benefits of the system. These builders represent a significant percentage of annual new housing starts, and they could become the initial customer base for the PnP system when introduced to market.

The following outcomes represent key feedback from builders related to the acceptance and adoption of the PnP system:

- Overall, builders are intrigued by the PnP concept and generally accept it because of existing familiarity with the cross-linked polyethylene (PEX) home-run plumbing system
- Builders are interested in the PnP system as a unique strategy that could simplify the HVAC design and installation process and reduce construction cycle time and schedule overruns.
- The opportunity to more cost-effectively install ductwork inside the conditioned space of the home is a big added value to builders, especially in the California market because of upcoming Title 24 requirements.
- If the calculated net cost savings from installing the PnP system compared to traditional systems (see Section 3 of this report) is accurate when a commercial product is available, this would be a great advantage for builders.
- There is skepticism that a commercial product using plastic ducts would be accepted by the building codes and that homeowners could view plastic ducts unfavorably.
- Overall, these builders are willing to consider the PnP system as a replacement to their traditional systems once a commercial product is available, and they would be willing to validate the performance of a working prototype in a test home or pilot project.

Working through the Alliance, IBACOS also collected input from national, regional, and local production homebuilders on the attitudes and values they hold toward the construction and marketing of high performance in their companies. These inputs were collected through two primary studies conducted by the Alliance: the 2015 "Builder Benchmark Study"[6] and the 2016 "Cost of Quality Study."[7] In these studies, builders were asked about their priorities and activities related to a variety of performance criteria that include safety, health, comfort, durability, efficiency, responsibility, connectivity, and affordability. These builders were also asked how their quality dollars are being spent—that is, what amount of investment is going toward proactive (quality assurance) or reactive (reserves, callbacks) activities to ensure the needed level of quality in their homes. These study results helped to set the backdrop for a construction climate where an improved air distribution system such as the PnP system would be accepted and valued by the market.

[6] This is a proprietary study by the Housing Innovation Alliance; contact the Alliance for more information at http://www.housinginnovationalliance.com/connect/.
[7] This is a proprietary study by the Housing Innovation Alliance; contact the Alliance for more information at http://www.housinginnovationalliance.com/connect/.

The following points represent key outcomes of builder engagement related to the PnP system:

- Most builders are sticking with code-level performance.
    - Relevance: The PnP system must clearly comply with the building code with a net cost equal to or better than a traditional system and with equal or better performance.
- Energy efficiency is the top performance value being marketed by all builders.
    - Relevance: The PnP system must tell a compelling energy-efficiency story.
- Builders direct between 40% and 80% of revenues toward construction costs.
    - Relevance: The PnP must offer significant net (material and labor) cost reductions.
- On average, each site supervisor of construction oversees 13 homes on a daily basis.
    - Relevance: Opportunities for simplification of the construction process are significant.
- The target cycle time for constructing a home ranged between 55 and 135 days.
    - Relevance: Faster installation is a key benefit of the PnP system.
- On average, actual cycle time was between 10% and 20% higher than the target.
    - Relevance: Faster installation is a key benefit of the PnP system.
- On average, between 10 and 15 days are built into the construction schedule for inspections and rework.
    - Relevance: The PnP system could reduce callbacks due to HVAC system installation defects and failure.
- On average, between two and four legitimate warranty items are reported by each homeowner following move-in.
    - Relevance: The PnP system could reduce HVAC system failures and subsequently reduce warranty costs.
- Between $150 and $8,000 are set aside on reserve per unit to cover anticipated warranty service, repair, and replacement following move-in.
    - Relevance: With proven performance success, builders could reduce reserve dollars per home and increase annual profits.

From these results, it is evident that opportunity exists for builders to promote the energy efficiency and comfort performance of their homes to target new customers and improve sales. Builders are spending money on both proactive and reactive quality management, which could be reduced by implementing measures to reduce cycle time and simplify the construction process. The PnP system could help builders reduce costs and ensure occupant comfort, thus improving their profit.

## 5.2 Consumer Attitudes and Values

Through the Housing Innovation Alliance, in 2015 IBACOS conducted a survey of more than 1,200 consumers from across the United States to better understand their values and attitudes related to housing, including the comfort, energy, durability, health, and safety performance of their homes. These data can be helpful to inform builders how to position houses with high-performance features, such as HVAC with the PnP duct system, to consumers, and they can help builders determine regional differences in consumer attitudes that might indicate where the system will be more highly valued. A summary of these results is provided here.

- Comfort performance of the house was “Very Important” or “Critical” to more than 75% of respondents; efficiency was 65%; safety ranked highest (80%); health was approximately equal to comfort (77%).
- Fresh, well-circulated air was the top response on how a home should contribute to health.
- Natural light and a thoughtful design/open floor plan were the top comfort needs, followed by draft-free, quiet, and feels personalized; uniform inside temperature was a moderate comfort need.
- Overall energy efficiency/lower utility bills and efficient heating and cooling systems were the top choices for what matters most in the efficiency of a home.
- Of the attributes that the home comfort system would provide, most respondents indicated that control over how the inside of the home feels is the most important attribute of the system; this was followed by ensuring that the air in their homes does not feel “stale” or “stagnant”; next, that their homes stay at the conditions they set no matter what happens outside; followed by the desire to set different climate preferences in different rooms in the house

## 5.3 Identifying Building Code Obstacles

The primary duct material that was explored in this project for use in a PnP system was PVC plastic. This material is inexpensive and readily available at any building material supplier; and because of the smooth interior (less friction and resistance to airflow), smaller available diameters, and ease of assembly, it would make an ideal duct material for the PnP system. However, PVC plastic is currently not accepted for use in low-rise residential buildings as an air duct material because of the current flammability and smoke development requirements in the code; therefore, this project explored the use of alternative duct materials that are currently available off the shelf and could be acceptable for use in a PnP duct system. Some of these materials included flexible duct, metal duct, duct board, and other nontraditional but readily available and code-approved materials. Some of these materials proved to be feasible options for the PnP system, which would enable the technology to more quickly go to market.

In parallel, the code community was engaged to gain acceptance for the use of PVC plastic ducts for residential air distribution systems. Ambiguous duct material requirements in the 2015 International Residential Code make the use of lower cost, higher performing plastic duct systems unnecessarily difficult or impossible, depending on interpretation at the local jurisdiction level. Tightly fitted assembly of plastic ducts inherently limits air leakage, and these duct materials are commonly available in appropriate diameters or other cross-section dimensions for low-load houses. Unambiguous building code approval of plastic air ducts would be a good alternative to make it easier to comply with ACCA *Manual J*, *Manual S*, and *Manual D* requirements (Rutkowski 2006; Rutkowski 2009a; Rutkowski 2014) and easier for code officials to inspect for compliance.

Ducts distribute air in our homes and are typically made of metal, fiberglass, and polyethylene plastics that are covered with fiberglass to meet the codes and standards requirements. PVC and acrylonitrile butadiene styrene (ABS) plastics have much higher flame spread and smoke-developed indices ratings because there is an abundance of fuel that can combust and develop smoke, per Charlotte Pipe and Foundry's *Plastics Technical and Installation Manual* (2017). This is one reason why thin, single-lined, non-insulated flex ducts meet the UL 181 Class 1[8] air duct requirements of 25 flame spread index and 50 smoke-developed index: they burn very quickly and do not develop any significant amount of smoke—basically, they burn, then extinguish very quickly. With a thicker and more rigid plastic pipe, there are concerns regarding their fire and smoke performance, yet the conditions by which these materials would or would not be acceptable as ductwork are not clearly defined in the code. In addition, alternate design scenarios where these materials could be allowed have not been extensively explored or documented in code-related discussions or in formal interpretations by the code body.

In fact, plastic air ducts seem to be "technically" allowed under International Residential Code 2015, Section M1601.1.1, but often they are rejected at the local jurisdiction level because of a lack of specificity, clarity, and coherence, particularly in relation to other parts of the International Code Council building and mechanical codes. Given the apparent ambiguity and inconsistency, an approach is needed to engage stakeholders to agree on the ultimate fire performance–related issues and to develop a strategy for revising the International Code Council duct material and duct systems code provisions.

IBACOS, in collaboration with the U.S. Department of Energy and the Pacific Northwest National Laboratory, engaged a group of code officials and code experts, including members of regional energy-efficiency organizations, in an Expert Working Group to help the residential construction community address key HVAC performance needs in homes and to potentially resolve the existing ambiguity in the International Code Council codes around the use of plastic ducts. The working group was tasked with completing the following primary activities:

1. Hold an expert session webinar to introduce the technology and discuss the existing code issues.
2. Complete a questionnaire to define current perceptions around the use of plastic materials in residential duct systems.

[8] UL 181 provides requirements that apply to materials used as air ducts and air connectors (fittings) in accordance with the International Code Council model codes and the National Fire Protection Association standards. Class 0 air ducts and connectors have zero surface-burning characteristics, whereas Class 1 air ducts and connectors require a maximum flame spread index of 25 and a maximum smoke-developed index of 50.

3. Peer review any proposed changes to the International Residential Code 2021 around this issue.
4. Peer review a new U.S. Department of Energy Code Compliance Brief on this issue to be published on the U.S. Department of Energy's Building America Solution Center website.

The expert session webinar was held on Jan. 17, 2017, and 10 code officials and code experts participated in the event along with IBACOS and Pacific Northwest National Laboratory. IBACOS presented the background information on the code issue related to the use of plastic ductwork, and the Pacific Northwest National Laboratory presented on the upcoming Code Compliance Brief being developed and the other resources available through the Building America Solution Center website. The message was clearly communicated that the code requirements are needed for the life safety of the building occupants and that because of this, fire spread and smoke development are the primary concerns. In the event of a fire, enough time must be provided so that the occupants can safely egress the building and so that the firefighters can safely extinguish the fire. The goal is to define the design conditions that will allow for the use of plastic duct materials while simultaneously meeting these essential life safety requirements.

The questionnaire was sent to the participants before the expert session, and six participants returned the completed questionnaire following the webinar. In summary, all the code officials who answered the questionnaire concluded that factory-made air ducts today must meet the UL181 Class 1 air ducts and air connector requirements and be accordingly labeled. If these code officials were presented with plastic ductwork that had received the UL181 listing, they would all allow its use. Although most PVC materials meet a flame spread index of 25, these same materials have a smoke-developed index of closer to 200. To improve the smoke-developed performance, additives or coatings would be needed, which would increase the cost of these materials. Despite the current International Code Council code requirements for UL181-compliant air ducts and connectors, not all ducts need to have the UL181 listing; the code allows non-factory-made ducts such as an air plenum made from wood, gypsum, or brick and mortar to be used because they are fabricated in the field.

Currently, components in the air distribution system or AHU that are made of plastics can be used, such as registers, cooling-coil drain pans, intake and exhaust ducts for high-efficiency furnaces, and inducer fans that are directly in line with the heat exchanger. Many of these components that are considered part of the appliance are tested per a separate standard for warm air furnaces, such as American National Standards Institute Z21.47 and UL 795, instead of UL181.

One of the fundamental questions in the questionnaire asked whether the main safety concern with plastic ductwork was with fires (i.e., a combustion source) originating inside or outside the duct. The response from code officials was that it did not matter: the duct material must meet the UL181 standard in both instances. The reason for this is that the ducts are long and connect rooms within a home, and thus they have the potential to spread flame and smoke from one room to another. This is one of the reasons why separate appliances and other furnishings in the house can be plastic: they do not connect rooms together, and therefore when they burn they are less likely to spread flame and smoke throughout the house. It is possible that a PnP duct system might negate this concern if it does not directly connect rooms in a home because it runs directly from the AHU to the terminating location.

Another reason plastic ductwork might be problematic is because it distributes air, which might contribute to spreading the flame and smoke; however, if an automatic shutoff were available at the furnace in the event of a fire, the code officials indicated that this might be an acceptable solution to prevent forced-air driven flame and smoke spread.

The following points summarize most responses by the code officials who returned the completed questionnaire regarding the major challenges to allowing the use of plastic ducts in homes:

- Testing needs to show the acceptable limits where flame from the equipment might catch the plastic duct on fire; that is, could a minimum stand-off distance of perhaps 2–3 ft of noncombustible duct from the equipment and an automatic burner shut-off prevent the plastic duct from igniting?
- Test and demonstrate the flame spread/smoke-developed time and temperature limits for plastic ducts.
- Test and demonstrate the elapsed time for flame to penetrate the plastic duct from the exterior; prove that the home must be "fully engaged" in flame before the duct is compromised. (IBACOS note: It could be relatively easy to demonstrate that there must be a large fire in the house before the plastic duct is compromised and that sufficient time will be available for the occupants to be notified of the fire and egress the house.)
- Determine the costs to meet these testing requirements.
- Electrical wire has overcome this obstacle, and it can be routed through ductwork, walls, and floors; plastic ducts will overcome this obstacle too.
- Fire needs air and fuel—if the air is cut off, then the spread is limited (i.e., an automatic burner shutoff might be a viable solution).

In summary, work remains to achieve approval for PVC and other low-cost plastic ductwork in residential buildings, but in the meantime, other off-the-shelf duct materials and products exist that can be successfully used to achieve the technical objectives of the PnP duct system and enable delivery to market.

## 5.4 Industry Event Feedback

IBACOS presented on the PnP system at four industry events: the 2015 Alliance Technical Summit, the 2016 Alliance PnP webinar, the 2016 Alliance Innovation Summit, and the 2016 Pennsylvania Housing Research Center's 3rd Residential Building Design & Construction Conference. Each of these events provided the opportunity to share information on the current project and get feedback from the event participants to help inform the value and direction of this research.

### 5.4.1 2015 Alliance Technical Summit

At the 2015 Alliance Technical Summit, IBACOS presented on the PnP system. This event provided the first direct opportunity to engage with builders and manufacturers and to gauge their general perception of the value this concept could bring to the market. Several individuals from national, regional, and local production homebuilding companies expressed enthusiasm in the PnP system as a possible means to help them cost-effectively bring ductwork into the conditioned space of their homes. There was general acknowledgement of the code barrier related to the acceptance of plastic ductwork in homes and the need to overcome these barriers before the value of the PnP system could be fully realized.

### 5.4.2 2016 Alliance Webinar

In 2016, IBACOS presented a webinar on the PnP system through the Alliance and received the following questions and feedback from the builders and building product manufacturers:

- Questions arose about the potential installation labor savings of the PnP system compared to trunk-and-branch duct systems. Additional questions included: What would be the learning curve for the trade contractors installing the system? Are there any critical constructability issues to consider? What would be the overall cycle time benefit of the PnP compared to trunk-and-branch systems? Can the PnP system more cost-effectively meet upcoming California Title 24 requirements?
- Could a wider diameter PEX-type duct be used instead of a rigid plastic material (e.g., such as plumbing pipe but with a wider diameter)?
- Would the AHU used for the PnP system be a typical, current, off-the-shelf unit or a specialized small-diameter system (e.g., Unico)?
- Would (or could) an enthalpy-recovery ventilator or heat-recovery ventilator be used with this system?
- Would the system be able to address high humidity concerns in a high latent heat environment (i.e., the humid Southeast)?
- Will the PnP system incorporate any "smart" monitoring associated with system performance, i.e., dual or multiple zones? Can the system balance itself more intelligently than the traditional method by comparing temperatures (via multiple, remote thermostats) with actual airflow performance?
- Will there be any issues with condensation build-up (such as in an unconditioned attic in the winter) as heat is pushed through the PVC?
- What is the noise impact of the PnP system? Will there be increased noise (decibels) in transitioning from smaller diameter (2-in.) ductwork to a larger register opening?

Installation time and labor savings of the PnP were evaluated compared to a trunk-and-branch duct system along with the constructability implications to the trade contractors that would ultimately be installing this system in homes. The labor savings were shown to be close to 50%, which could translate to a cycle time benefit of 1–2 days on a typical single-family new unit.

Because the PnP system is designed to be integrated into the floor and wall framing of a home, it could be an ideal solution for bringing ducts inside the conditioned space of the home and help meet the upcoming requirements of California's Title 24.

The team identified some limitations to fully rigid duct materials (e.g., schedule 40 PVC) when installing these products in the floor structure of a house—for example, the materials were difficult to manipulate in between the floor web trusses, requiring shorter lengths to be used (too labor intensive) or the construction of a "bulkhead" below the floor structure to enclose the ducts. When using semirigid materials such as PEX piping, this would not be a problem. Currently, PEX with a wider diameter is not available, and PEX itself does not meet the UL 181 Class 1 circular duct requirements, but if these criteria were met, then this could be a viable solution.

A small-capacity, modulating gas furnace was used for the lab house testing in this project. This system is available off the shelf through certain distributers. Ideally, the PnP system would be a viable duct system for any smaller capacity air handling equipment. It is possible to create a specialized system for specific equipment, but this project focused on an application for off-the-shelf equipment.

It is possible for an energy recovery ventilator or heat recovery ventilator to be used with this system. The impact of using these ventilation systems would need to be included in the load calculations that are completed prior to designing the duct layout.

Although humidity was not a comfort factor evaluated in this project, theoretically the PnP duct system should be sufficient to address the latent load in hot, humid climates if the cooling equipment has been properly sized to these loads (and supplemental dehumidification added if needed); however, this performance parameter has not been modeled or tested and would need to be verified.

Although "smart" controls or balancing dampers were not part of this current study, it is certainly possible or advisable to explore the incorporation of these components with the PnP system in the future.

Because ductwork is installed in conditioned space, there should not be an issue for condensation potential. If there is a failure in the enclosure and unconditioned air leaks into a cavity, there might be issues with condensation; however, this is present for any uninsulated duct system, including sheet metal.

The scope of this work did not include an analysis of the noise generated from components. Past research has shown that noise is not a major issue with the lower airflows in small-diameter duct-work (Poerschke and Rudd 2016). Further, sound generation and transmission is very dependent on final product design and shape. Currently, the prototype parts do not generate significant amounts of sound; however, the final product should keep noise generation as a design constraint.

### 5.4.3 2016 Alliance Innovation Summit

Feedback from the 2016 Alliance Innovation Summit was like feedback provided at the 2015 Alliance Technical Summit. Builders were excited to learn more about the system as a potentially more cost-effective means to bring ductwork into conditioned space and to meet the

California Title 24 requirements. At the time of the 2016 Summit, IBACOS was already engaged in dialogue with a manufacturing company around the potential commercialization of the system (see Builder and Manufacturer Commitment below), so our conversation with other manufacturing participants at the summit was limited.

#### 5.4.4 2016 Pennsylvania Housing Research Center's 3rd Residential Building Design & Construction Conference

In March 2016, IBACOS presented on the PnP system at the Pennsylvania Housing Research Center's 3rd Residential Building Design & Construction Conference at the Pennsylvania State College State College campus. Focus of the presentation was on the current PnP project results and results from a case study of small-diameter duct systems (the Unico System) installed in two Denver, Colorado, town houses. One of the key messages of the presentation showed that both the installed small-diameter systems in Denver and the PnP lab and field tests achieved equal or better room-to-room temperature uniformity when compared to conventional trunk-and-branch systems. This was an important message to communicate to the conference participants—which consisted primarily of Pennsylvania builders, code officials, and researchers—to help build greater awareness in the industry that smaller diameter ductwork can provide the levels of comfort needed by occupants in their homes.

Comments and feedback from the participants included the following:

- Appreciation of the way the PnP approach brought ductwork into conditioned space; this is a strong advantage of this system.
- Interest in the value of adding insulation to the ducts (to reduce heat loss/gain and improve comfort in terminal rooms), despite the installed ductwork being in conditioned space.
- People assumed that the static pressure would be high in the system (i.e., > 1.0-in. water column), which was not observed during the testing.

Benchtop testing and evaluation in the unoccupied lab home as part of this project indicated that temperature loss through the ductwork had a significant impact in some instances on the supply outlet air temperature at the duct termination. When installed inside the conditioned space of the house, this temperature loss/gain had less significance on the resulting room-to-room temperature uniformity in the home. Although installing insulation on the duct would help maintain uniform supply outlet temperatures, duct material selection might have a greater impact to overall performance of the system.

### 5.5 Builder and Manufacturer Commitment

IBACOS engaged with several national, regional, and local production homebuilders through the Alliance events and activities and identified a cross-section of these builders that are interested and willing to explore the possibility of demonstrating a PnP duct system when this system becomes available on the market. A primary driver of their interest in the system is the potential benefits it could provide to more cost-effectively bring ductwork inside the conditioned space of the house. California's Title 24 is driving this requirement in the California market, which is a very large market for many of these builders. The PnP system could be a more cost-effective way to address this issue for builders. At the time of this report, the PnP system is in the prototype stage of development and is not yet available as a product on the market, so these interested builders cannot commit to install the system now; however, the top five builders that are willing to stay engaged represent a range of home construction volume—Top 10 and Top 20 levels of volume, leading regional builder, and local/boutique builder.

In June 2016, IBACOS engaged a building products manufacturing company in discussions around establishing a partnership to further develop and commercialize the PnP system and to bring this system to market. The discussions are ongoing at the time of this report's publication, with the goal of establishing a partnership agreement in early 2017 to move forward with the development of the PnP system. Fundamental to this commercialization effort is establishing the potential market opportunity for the PnP system, and initial activities will be directed toward this essential goal. The PnP system has the potential to change the nature of HVAC system performance and provide a more cost-effective means to install a high-performance system that will deliver customized comfort throughout the home. With a manufacturing partner on board, the PnP system could represent a significant advancement in the residential HVAC market.

# 6 Conclusion

The goal of this project was to develop a simplified residential air delivery system that is a solution to air distribution and comfort delivery issues in low-load, production-built homes and is emergent on the industry. The specific objectives of this project include the following:

- Develop a straightforward design methodology and companion guidance documents that will allow an HVAC technician to quickly produce the equivalent of an engineered design for a simple, field-assembled, small-diameter, rigid-material residential duct system, presently called the PnP air delivery system.
- Demonstrate the advantages of the simplified air delivery system compared to traditional trunk-and-branch residential duct systems.
- Demonstrate tangible progress to overcoming code and standard barriers associated with implementing this technology in residential homes.
- Secure written commitment from at least one manufacturer partner to pursue product development and at least one builder partner to demonstrate the technology based on preliminary findings.

A new design methodology for the PnP duct system was developed as part of this project to replace existing design methods that are not appropriate for the PnP home-run approach. For this new methodology, a designer would use a calculation spreadsheet that selects the number of equal-sized ducts needed to condition each zone. The number of ducts needed would be based on the heating and cooling loads calculated for each zone and the duct total length and number of elbows needed to reach each zone. Adjustments to the design airflows would be made based on the type of duct material that is selected.

Lab testing and modeling was completed to determine the appropriate materials and duct diameters that are needed to adequately condition homes built to the IECC 2009 and 2012 enclosure requirements. Most homes up to 4,200 $ft^2$ in climate zones 3–5 could be adequately conditioned with 3-in.-diameter smooth ductwork, whereas smaller homes (less than 2,200 $ft^2$) or homes with a very small space-conditioning load (built to certification standards of the Passive House Institute US) could be conditioned using 2.5-in. or 2-in. smooth ductwork.

A time and motion study was completed to determine the labor and material costs of the PnP system compared to a traditional trunk-and-branch system. This study provided useful insight into the installation and cost benefits that can be achieved with the PnP strategy compared to a traditional duct system. The first advantage that was realized was that fewer amount of materials were needed for the installation of both PnP systems compared to the traditional trunk-and-branch system. The trunk-and-branch system required 18 different components, whereas both PnP systems required only 5 different components. This simplification of materials would likely make it much easier to manufacture, stock, order, and process the necessary components. The material cost for the 2.5-in. pipe is unusually high compared to the 2-in. pipe. The main reason for this is that the 2.5-in. size is not very common and is typically used only for furnace combustion pipe venting. Therefore, the 2.5-in. pipe along with all the fittings cost substantially more than the standard-sized piping. Also, the 2.5-in. PVC piping was a schedule 40-rated pipe. Ideally, the piping that would be used would be made of a thinner-walled pipe in the schedule 10–15 range, which could potentially reduce the material costs.

The smaller 2-in. PnP system was less costly because the pipe was a more common size and available off the shelf at local supply warehouses, and the bulkhead is not needed to conceal the pipe.

All three systems used a bottom-feed central air return strategy in the AHU closet. Additional savings for the PnP system compared to the trunk-and-branch system might also be realized for the return air strategy. To ensure proper return air from enclosed rooms, the traditional trunk-and-branch system would require over-the-door transfer grilles or a jump duct between the enclosed bedrooms and the common hall space. The estimated cost for either a transfer grille or jump duct kit is between $45 and $75 per unit. This cost would have an impact on the overall system cost. Because of lower airflow into the rooms, the PnP systems could avoid the additional cost of the return air ducts by using door undercuts as a means of return air transfer.

In this study, all ductwork was installed in conditioned space and therefore was not required by codes to be insulated. The traditional trunk and branch system was installed with flexible ductwork that includes the integrated R-4.2 fiberglass insulation and vapor barrier jacket. This ductwork was selected for the study because it is the most widely used type in residential construction today. Because this study focused only on the installation of the ductwork rather than the insulation, both the 2.0-in. and 2.5-in. PnP duct systems did not have any type of insulation installed; however, in some regions of the country (such as hot, humid climate zones), insulating the ducts might be specified to combat potential condensation issues. If insulation is included on the PnP duct systems, additional costs would be incurred for these materials and the labor to install them.

Table 37 presents a summary of the time and motion evaluation results for the traditional trunk-and-branch, 2.5-in. PnP, and 2-in. PnP systems.

**Table 37. Systems Cost Comparison**

| Duct System | Hours | Labor Cost @ $33.35/h[a] | Material Cost | SKU'S | Length of Duct | Cost of Ductwork System |
|---|---|---|---|---|---|---|
| Trunk-and-branch | 11.95 h | 398.53 | 419.54 | 18.00 | 35-ft trunk | |
| Ceiling chase | 5.7 h | 190.65 | 67.55 | | 50-ft flex | |
| **Total** | **17.65 h** | **589.18** | **487.09** | | | **1,076.27** |
| 2.5-in. PnP | 4.18 h | 139.51 | 613.94 | 5.00 | 210 ft | |
| Ceiling chase | 5.7 h | 190.65 | 67.55 | | | |
| **Total** | **9.8 h** | **330.16** | **681.49** | | | **1,011.65** |
| **2-in. PnP** | **5.83 h** | **194.55** | **440.27** | **5.00** | **250 ft** | **634.82** |

[a] Labor rate based on skilled worker classification in the 2015 *RS Means Residential Cost Data* handbook and does not include overhead and profit

A detailed EnergyPlus model was developed to evaluate the performance of the PnP system compared to a traditional trunk-and-branch system in achieving temperature uniformity throughout a house compared to the central thermostat. Overall, the simulation results suggest great potential for the PnP duct system. In most of the cases simulated, the PnP duct system performs as well as or better than the traditional trunk-and-branch system. Time periods when the PnP system did not perform as well were likely because the summer design airflow was significantly greater than the airflow needed in the winter, thus causing some zones to be over-conditioned in the winter. Although the percentage of time the temperature difference from one room to another was beyond industry standards might have been high for some of the cases, this is congruent with trends measured in the field. A three-story townhome showed an average room-to-room temperature difference of 6.6°F during a 9-day summer period (Poerschke, Beach, and Beggs 2016).

A strong conclusion of the simulation work is that differences in seasonal and peak loads are a greater driver in comfort than the system, whereas the PnP system was less sensitive to the change. This disparity was most pronounced in climates with large differences between heating and cooling loads. Poor winter performance by both systems shows the need for seasonally rebalancing airflows. Currently, many installed duct systems do not allow for easy rebalancing each season. If balancing dampers are installed, they are typically in an inaccessible location such as the attic or basement, or they are hidden behind drywall. Measured data from a cold climate Passive House (Herk, Poerschke, and Beach 2016) and three-story town houses (Poerschke, Beach, and Beggs 2016) also show this need.

Field measurements show that door undercuts might be a sufficient return air pathway for the PnP system. No measurable difference was observed in delivered airflow to rooms with their doors open or closed. Greater static pressure in the duct system resulting in lower room airflows are likely causes for this behavior. As more ducts are added to a zone, because of larger size or less envelope efficiency, the need for a dedicated return strategy might manifest.

The total pressure in the splitter manifold for the PnP system was lower than initially expected. At 259 CFM, the 2-in., 12-duct system installed in the unoccupied test house required 0.32-in. water of available static pressure. Large reasons for this were the use of smooth-walled plastic ductwork and a compact layout with a centrally located AHU. Systems with larger ducts or more ducts could easily accommodate larger airflows. Although a complete fan energy analysis was not part of this study, it is an important aspect that will be studied in the future.

AFN modeling is a relatively unused component of the EnergyPlus engine, particularly in residential energy analysis. Current trends in simulating comfort performance in low-load homes might increase interest in using AFN. Practitioners will also gain the ability to diagnose the role of architecture in comfort by enabling the study of interior configurations and layouts on comfort performance. Although AFN has powerful capabilities, it requires care when setting up each component for the simulation to run at all, let alone yield valid results. Although getting a simulation to run is an achievement unto itself, it must be compared to data sets to ensure that the results are realistic.

To facilitate the debugging process, the team developed some methods that allowed for examination of model inputs and associated outputs as they related to the AFN. One important tool was a graph network generated simultaneously as the models were created that visualized the node connections and AFN component parameters. This visualization allowed for pinpointing issues in a complex network of hundreds of components, to be able to connect the dots, so to speak, when wading through a sea of objects. One model file was nearly 20,000 lines, with all connections managed solely through variable names. It will be important for practitioners making use of new tools to share their lessons and workflows as they navigate these complex models; this will facilitate the wider adoption of new modeling capabilities in EnergyPlus.

Although EnergyPlus and AFN were successfully used in this project to simulate the air distribution system and zone air temperatures in a house, significant hurdles exist for everyday practitioners to use these tools. EnergyPlus is primarily configured for energy consumption simulations in the commercial building industry. As such, there is significant overhead when setting up a simple residential HVAC system, which might turn away some would-be users. Additionally, by default, EnergyPlus does not simulate real-world thermostat performance with cyclic fan behavior. Although it is unlikely that the developers of EnergyPlus will deviate from serving their primary industry, there is a rising interest and need to serve practitioners who would like to simulate comfort in residential buildings.

This work represents a starting point for comparing the performance of the PnP duct system to a trunk-and-branch flex duct system. One shortcoming of the research presented here is that only one floor plan was simulated. Future work could consider different house types and geometries (e.g., slab on grade, single story versus two story).

This study did not consider the energy impact of the PnP duct system. Because the duct system uses smaller diameter ducts, it is expected that the system might use greater fan energy at peak conditions. The equipment used in this study was single-stage equipment to simplify the modeling process. A future study could consider the impact of variable-capacity equipment on comfort and energy use. Equipment that can lower its fan speed to directly match the house load would mitigate some of the energy penalty from using smaller diameter ducts (which could also be said for a trunk-and-branch system).

One of the more notable conclusions from this work was the impact that differences in seasonal loads and airflow requirements can have on comfort. The industry is well aware of this issue; however, there is typically not a robust solution applied. Using the simulation framework built during this project, the duct system design could be constructed using the summer loads and the winter loads. Each design could then be compared in a best-case scenario. Another scenario would be to run a single duct design but with seasonal balancing dampers installed to emulate a manual rebalance at the beginning of each season.

Another goal of the project was to engage the industry and solicit feedback on the PnP duct concept to the residential housing industry. The primary goal of the market engagement activities was to gain interest, acceptance, and demand for the PnP air delivery system. Outcomes of the market engagement activities demonstrated real interest in the technology and highlighted key areas where this technology could help builders improve performance and increase their bottom line. Where codes and regulations are pushing for higher performance and requiring ductwork to be installed inside conditioned space (such as in California's Title 24), the PnP system could be a cost-effective means to achieve these required targets. As a continuation of this study, the benefits of installing the PnP system inside the attic compared to a typical attic system will be evaluated as well, given the challenge many builders are facing with bringing ducts inside conditioned space. With reduced labor needed to install and commission the PnP system, builders and their trades can reduce costs while achieving good comfort in their homes. The primary barrier to the development and adoption of the PnP system is the current code barrier around the use of plastic ductwork, which must be addressed before the full potential of this system can be realized.

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# Appendix A: Airflow Network Setup Lessons Learned

Geometry has been modeled in Rhinoceros NURBS three-dimensional modeling software (Rhino) as polysurface objects traced from architectural drawings. The model geometry was converted to EnergyPlus input using Python scripts in the Grasshopper plug-in for Rhino. HoneyBee was used to perform the solve adjacencies functions and to generate all the overlapping surfaces. The EnergyPlus input strings were used as static building blocks in individual models. Some components, such as the doors' opening factor, were modified between models, but most of the geometry coming out of Rhino was static among all models generated. Surface adjacencies, fenestration object association (doors and windows), and construction types (interior/exterior walls, ceilings, etc.) were solved and written to the appropriate parameters for EnergyPlus.

Constructions and materials were created and then extracted from BEopt 2.0 representing 2012 International Energy Conservation Code and the lab home specifications. The EnergyPlus objects were pulled out of the .idf files generated by BEopt. The construction types were then matched to the surfaces, subsurfaces, etc., of the geometry output from Rhino by type names.

The following diagrams illustrate how the AFN was hooked up for simulating the distribution system. The diagrams are taken from a DOT graph generated simultaneously with the simulation input files and contain graphic representation of the node connections and the distribution and mixing components connecting the nodes. These graphs were invaluable to diagnosing connection errors that cause simulations to crash because of pressure imbalances and unrealistic component parameters. These graphs in combination with node pressure plots were the most useful debugging tools. Figure 59 details the airflow network distribution and return hookup.

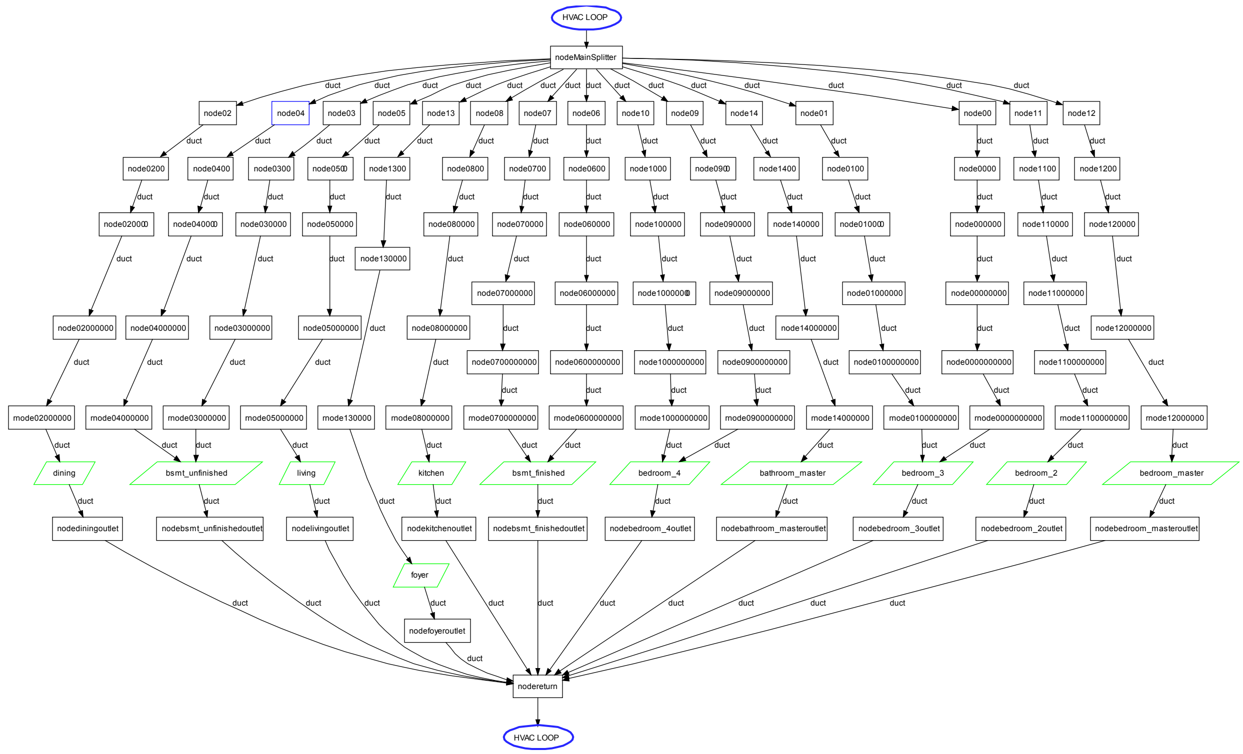


**Figure 59. Full AFN distribution and return diagram**

The AFN must be set up to connect at key points to the EnergyPlus Air Loop and Zone Equipment Loop. The following diagram illustrates the Air Loop connections, i.e., the HVAC system, and shows the connections and linkage to the EnergyPlus Air Loop. All the zone supply ducts originate from the main splitter node and return via the outlets from each zone to the main mixer node. More than one duct might supply a single zone, whereas only one outlet can return from each zone. If the zone has no actual connection, the return path can be a very small diameter duct to force the air to return through the connections between zones, such as doors and large openings.

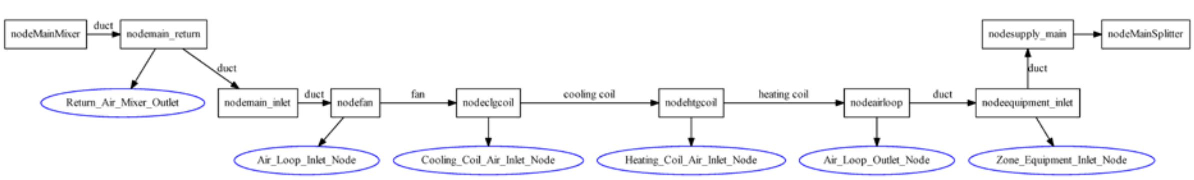


**Figure 60. Equipment Loop connections for AFN**

Figure 61 shows a detail with the return configuration that allows for air to return through the multi-zone mixing objects. Note the very small-diameter return ducts on all but the main return—foyer—zone. This forces the air through openings such as doors and horizontal openings rather than return ducts. Return ducts are necessary, but they can be modeled in this way for central return strategies.

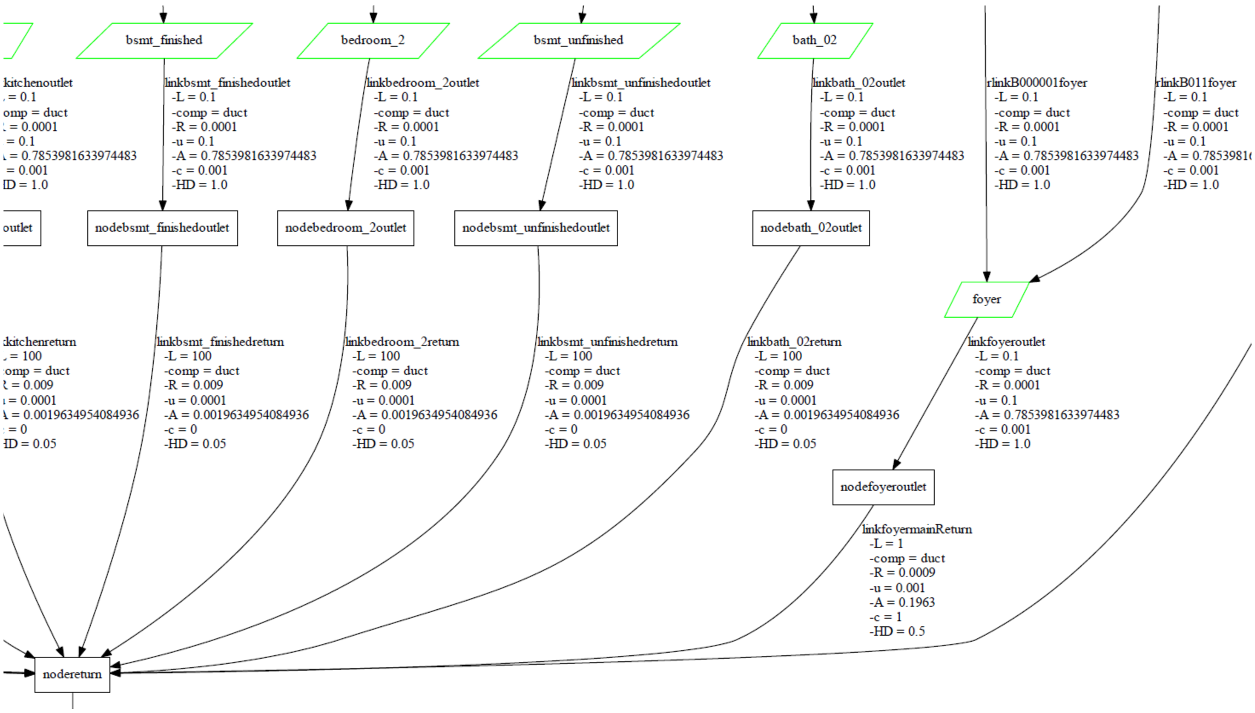


**Figure 61. Detail of AFN return hookup**

To connect supply ducts to conditioned zones, low-resistance duct segments are linked to the zones, then to outlets that are referenced in the HVAC loop. Figure 62 illustrates how this hookup is made in the AFN.

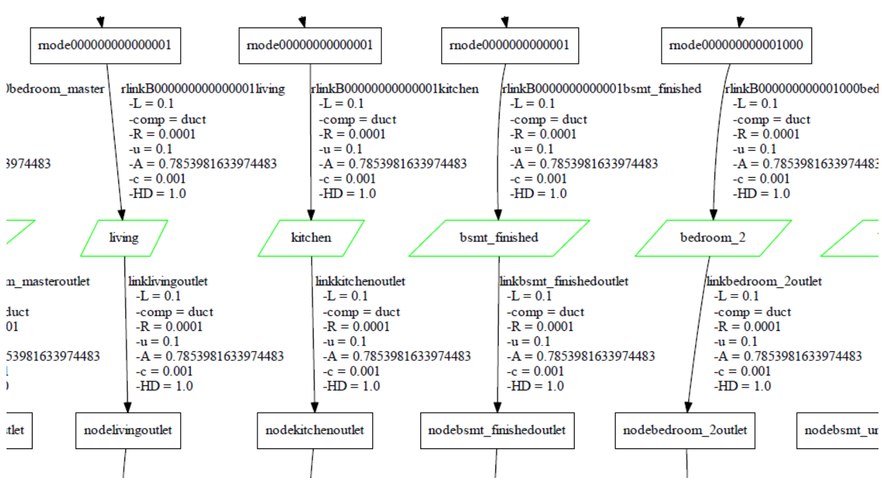


**Figure 62. AFN zone connection example connections**

All but the primary return zone in these models were restricted with essentially very long straws so the path of least resistance was through the adjacent zones and hallways rather than through the return duct itself. The return path then became a combination of simple openings, horizontal openings, and large openings.

Large openings and doors were modeled in the same way. They must be modeled as fenestration subsurface pairs in EnergyPlus, one of which must be associated with an Air Flow Network:MultiZone:Surface object, which has a DetailedOpening component applied.

To model duct leakage, simple leak components were used to connect to branch takeoffs to the floor cavity, where they were conceived to be located. Figure 63 details a single takeoff from the main trunk with a leak into the floor cavity. A coefficient of 0.002 was sufficient to achieve approximately 20% of total system flow.

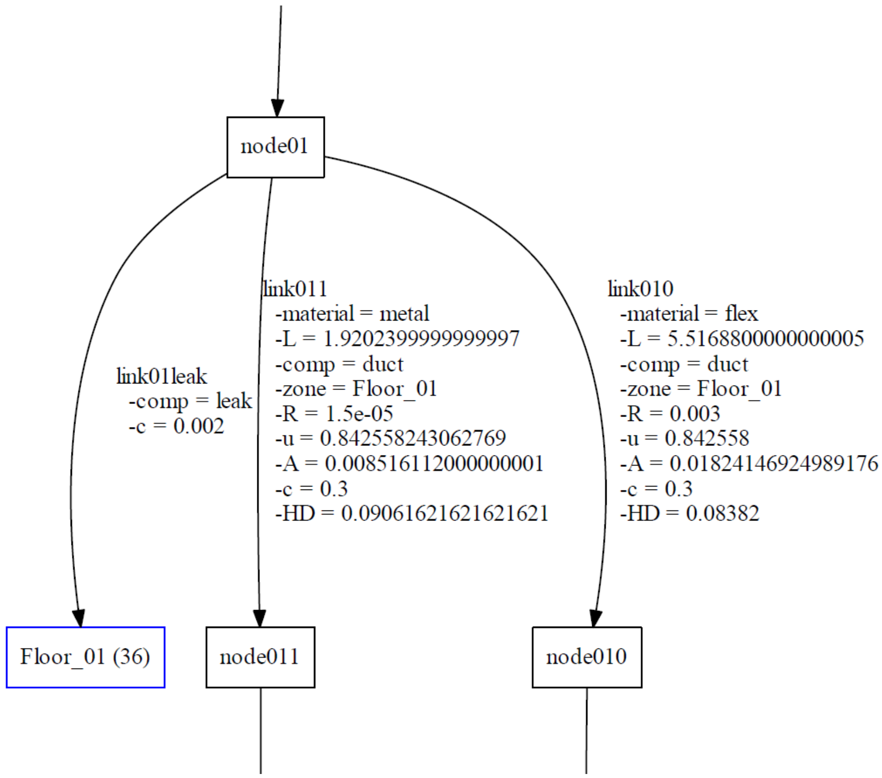


**Figure 63. AFN duct leakage example**

# Appendix B: Design Method Instruction Sheet

## Plug-and-Play Design Spreadsheet Instructions

The PnP duct system is composed of identically sized small-diameter ducts that emanate from a single central manifold box. The system is designed by determining the number of ducts needed to satisfy the load in each zone instead of sizing duct diameters according to load. This process greatly simplifies the design and installation process.

The designer should complete the following steps using standard Air Conditioning Contractors of America (ACCA) tools and the design spreadsheet.

- Complete ACCA *Manual J* load sizing for house. The total load in Btuh should be calculated for each zone. Zones with very low loads, i.e., small closets, might be lumped with larger, adjacent zones and not require their own duct. Paper calculations might be used or ACCA-approved calculation software. The spreadsheet will calculate the airflow required for each season's load by using a heating and cooling factor. The greater of the two loads is used for the duct design.
- Create a rough duct layout using the floor plan. The air handling unit closet should be centrally located in the house. Framing plans should be referenced to identify where ducts might be routed. All ducts should be located in interior walls and cavities in the insulation envelope. Outlet locations will be high-sidewall or ceiling mounted. High-sidewall outlets should be located on interior walls and directed toward exterior walls.
- Once the rough layout is completed, the approximate total length of each duct runout and number of elbows should be totaled. Elbows are all assumed to be 90° with a small sweep.
- Determine available static pressure based on manufacturer's data and ACCA *Manual S* (Rutkowski 1995; Rutkowski 2009a). The available static pressure accounts for the filter, coil, and other elements not in the supply side of the duct system. This value is used to calculate the available potential in the manifold to move air through the duct system.
- Duct material can be selected from three different choices in the drop-down menu. The flow characteristics for each duct material are based off measurements and will update when a new material is selected.
- Enter values into the design spreadsheet. The cells where values should be entered are shown in blue. The specific values to be entered are available static pressure, room names, heating and cooling loads (Btuh), length of duct and number of elbows, and duct material.
- The spreadsheet displays the number of ducts required in the final column.

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Notes:

Because of the use of smaller ducts, the total system airflow is limited. The expected upper range on the total house load is approximately 45,000 Btuh heating and 40,000 Btuh cooling. The exact range depends on equipment and duct system parameters (diameter and length) for each unique design.

The heating factor and cooling factor are equipment specific. Currently, the design method does not specify exact equipment. The intention is that a cooling airflow consistent with high-velocity equipment would be used (300–350 CFM/t).

The design spreadsheet calculates the flow through each duct and determines the minimum number of ducts needed to condition each zone. A total equivalent length is calculated by multiplying the number of elbows by the equivalent length of a single elbow and adding that value to the total duct length. The flow is calculated using the following equation:

$$CFM = \frac{P_A}{C * \ell}^{1/n}$$

where $P_A$ is the available static pressure (in. water column), $\ell$ is the total equivalent length (ft), $C$ is the flow coefficient per length (ft), and $n$ is the flow exponent. The flow coefficient and flow exponent are based on preliminary lab measurements for each material and diameter. Currently, data are available for 2-in. PVC pipe, 2.5-in. PVC pipe, and 3-in. flexible ductwork.

Design methodology spreadsheet:

## Plug-and-Play Home Run Manifold Design Tool

v 0.1

| | | |
|---|---|---|
| Project | | |
| Nominal CFM | 39 | (based on 30' L, 60 Pa) |
| Available Pressure | 0.35 | in. wc. (from manual S) (minus 0.1" for manifold) |
| Heating factor | 0.0231 | Btuh / CFM |
| Cooling factor | 0.0268 | Btuh / CFM |

| # | Room | Htg Load (Btuh) | Clg Load (Btuh) | CFM | Len (ft.) | Elb | Ducts |
|---|---|---|---|---|---|---|---|
| 1 | Master Bedroom | 2365 | 2316 | 55 | 29 | 5 | **2** |
| 2 | Bath 2 | 642 | 220 | 15 | 12 | 3 | **1** |
| 3 | Bedroom 2 | 2025 | 1500 | 47 | 15 | 4 | **1** |
| 4 | Powder | 798 | 620 | 18 | 22 | 3 | **1** |
| 5 | 1st Floor | 6489 | 4486 | 150 | 16 | 3 | **3** |
| 6 | | | | | | | |
| 7 | | | | | | | |
| 8 | | | | | | | |
| 9 | | | | | | | |
| 10 | | | | | | | |
| 11 | | | | | | | |
| 12 | | | | | | | |
| 13 | | | | | | | |
| 14 | | | | | | | |
| 15 | | | | | | | |
| 16 | | | | | | | |
| | Total: | 12319 | 9142 | 285 | 94 | 18 | **8** |

Select Material

2.5" PVC

| | |
|---|---|
| EL of 90 | 2 |
| Pipe Diameter | 2.5 |

Coefficients -- 2.5" PVC  CFM = (Pa/C*L)^(1/n)

| | |
|---|---|
| C | 0.00556 |
| n | 1.706 |

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